Open University Geological Society Journal

Volume 31 Numbers 1–2 2010

Editor: Dr David M. Jones
e-mail: journal@ougs.org

The Open University Geological Society (OUGS) and its Journal Editor accept no responsibility for breach of copyright. Copyright for the work remains with the authors, but copyright for the published articles is that of the OUGS.

ISSN 0143-9472
© Copyright reserved

OUGS Journal 31 (1–2) Edition 2010, printed by Hobbs the Printers Ltd, Totton, Hampshire

Committee of the Open University Geological Society 2009

Society Website: ougs.org

Executive Committee

President: Dr Dave McGarvie, Department of Earth Sciences, The Open University, Milton Keynes MK7 6AA
Chairman: Linda Fowler
Secretary: Sue Vernon
Treasurer: Bob Morley
Membership Secretary: Phyllis Turkington
Newsletter Editor: Karen Scott
Events Officer: Chris Arkwright
Information Officer: vacant at time of going to press

Branch Organisers

East Anglia (EAn): Wendy Hamilton
East Midlands (EMi): Don Cameron
East Scotland (ESc): Stuart Swales
Ireland (Ire): John Leahy
London (Lon): Jenny Parry
Mainland Europe (Eur): Elisabeth d'Eyrames
Northumbria (Nor): Paul Williams
North West (NWe): Mrs Jane Schollick
Oxford (Oxf): Sally Munnings
Severnside (Ssi): Janet Hiscott
South East (SEa): Elizabeth Boucher
South West (SWe): Chris Popham
Walton Hall (WHa): Tom Miller
Wessex (Wsx): Sheila Alderman
West Midlands (WMi): Linda Tonkin
West Scotland (WSc): Jacqueline Wiles
Yorkshire (Yor): Geoff Hopkins

Other officers

(non-OUGSC voting unless otherwise indicated)
Sales Officer (voting OUGSC member): Lesley Laws
Administrator: Don Cameron
Minutes Secretary: Pauline Kirtley
Journal Editor: Dr David M. Jones
Archivist/Reviews: Jane Michael
Webmaster: vacant at time of going to press
Deputy Webmaster: Martin Bryan
Gift Aid Officer: Ann Goundry
OUSA Representative: Capt. Alasdair Farquharson
OUSA Deputy Representative: vacant at time of going to press
Branch Organisers Representative: Don Cameron

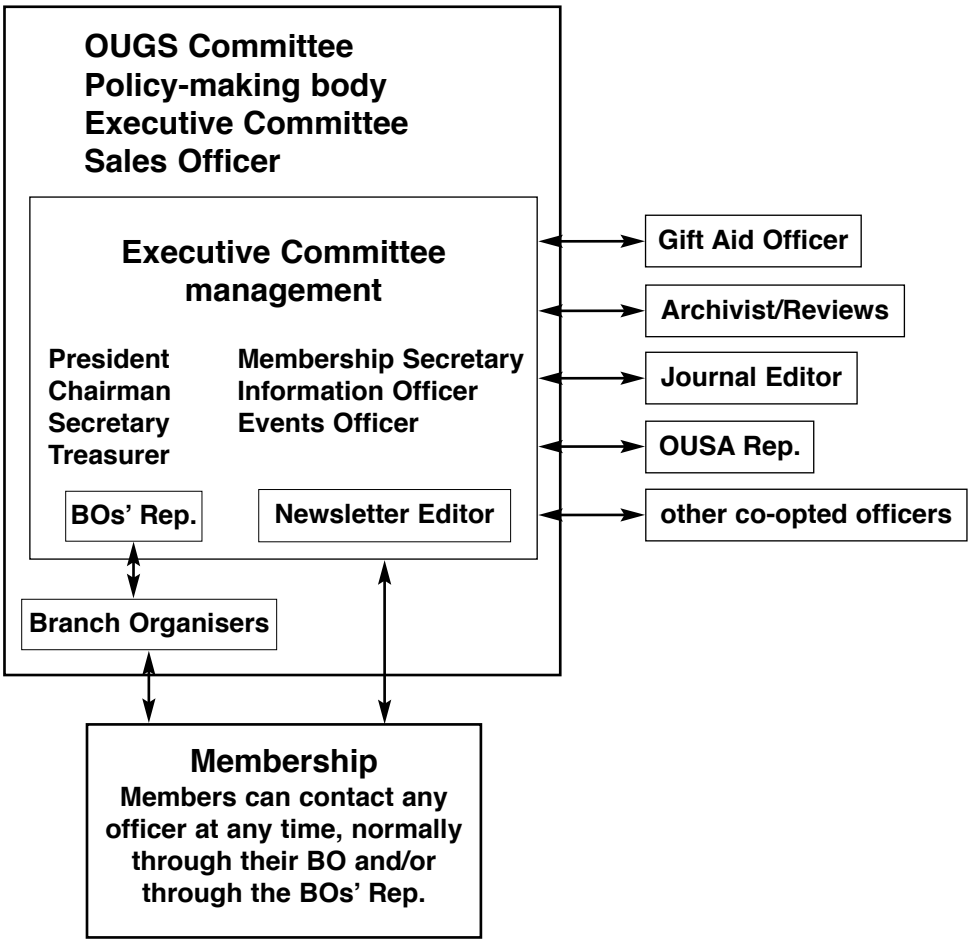
Vice Presidents

Dr Evelyn Brown, Dr Michael Gagan and Norma Rothwell

Past Presidents

1973–74 Prof. Ian Gass
1975–76 Dr Chris Wilson
1977–78 Mr John Wright
1979–80 Dr Richard Thorpe
1981–82 Dr Dennis Jackson
1983–84 Prof. Geoff Brown
1985–86 Dr Peter Skelton
1987–88 Mr Eric Skipsey
1989–90 Dr Sandy Smith
1991–92 Dr Dave Williams
1993–94 Dr Dave Rothery
1995–96 Dr Nigel Harris
1997–98 Dr Dee Edwards
1999–00 Dr Peter Sheldon
2001–02 Prof. Bob Spicer
2003–04 Prof. Chris Wilson
2005–06 Dr Angela Coe
2007–08 Dr Sandy Smith

DISSEMINATION OF INFORMATION PATHWAYS



Editorial:

Dear readers,

As your *OUGSJ* Editor I must first apologise profusely for the long wait you have had for this issue. There were unfortunately severe delays for many reasons, a principal one of which was the time it took to track down and secure the sources and permissions for the pictures used in this issue. For their perseverance and help with this matter I sincerely thank all the authors.

The first thing that I hope you noticed when you received this issue is its new cover. The aim is to use a standard background and typography, but to change the cover of each issue with a selected image from one of the articles in the issue; and to list the contents on the back cover.

The second thing I hope you noticed is that we have gone full colour. Traditionally, this is the issue — the 'first' in the year — in which we include the winning photographs of the Moyra Eldridge Photographic Competition, and you will find these in the un-numbered centre pages. You will also notice that this issue is combined as Numbers 1–2.

We held an excellent 2010 OUGS Symposium in Swansea this year. Since the 2009 Symposium in Leeds, the Executive Committee has had much discussion about our methods of procuring papers from the symposia for these issues. Formerly, this has involved our urging the speakers to produce papers from their talks. To many of them, with busy research programmes and academic duties, this has often proved difficult. In the past we have used our OUGS cassette recording equipment to record the talks, and have always offered to transcribe these for the speakers to use as a base for their papers. However, over the years we have had to face the fact that our equipment is increasingly out of date, often hard to accommodate to the much more modern recording set-ups in our symposia venues, and that it is a burden to our willing volunteer transcribers and also becoming increasingly difficult to find volunteers who still have cassette recorders and players!

We have concluded our discussions by deciding that we will continue to urge every symposium speaker to write a paper for the *OUGSJ*, but realise that we will probably no longer receive papers from all speakers. We are exploring technology to record and possibly even video the talks in the future, and publish these as pod-casts on the OUGS Website instead. The Swansea Symposium Organising Committee asked all the speakers to consider writing-up their talk for the *OUGSJ*, and after the Symposium I contacted every speaker several times about this, in the hope that we would be able to put together a Swansea Symposium issue by the end of 2010.

As it happens, there have been severe delays to the general 'spring' issue for 2010 that should precede the Symposium Edition, and the response from the Swansea speakers has been 'agreement' from a few of them, but otherwise, to date, silence.

With regret, I therefore have to tell you that it is not possible to produce a 2010 Symposium issue. Any papers that the speakers do write will be published in future numbers of the *Journal*, but not as a special symposium number.

We have therefore decided to use our resources to produce a modern journal in full colour, and I am happy to say that the images received for the papers in this issue make a splendid show for you.

Our spring AGM will have another Geoff Brown Memorial Lecture, and this will form the lead article in the first 2011 *OUGSJ*. It may also be that we produce only one issue per year, in colour. This will depend in part, of course, on the number of papers received — so please consider writing up your field trips and investigations, and explaining the geology to your fellow OUGS Members. Often, lectures delivered at Branch days of lectures also make suitable topics for short papers in the *OUGSJ*.

On October 9th I attended the Open University Open Day for 'Four Decades of Earth and Planetary Science' at the OU Department of Earth and Environmental Sciences. It was a thoroughly enjoyable day and there was a programme of lectures of particular interest. Personally, a favourite of mine was by Dr Ian Stewart of Plymouth University, who talked about 'How Earth Made Us'. In his talk Dr Stewart presented a splendid combination of palaeoenvironmental, geological, archaeological and historical evidence and lines of inquiry. An after-lecture enquirer asked Dr Stewart, 'Do we, as geologists, do enough to educate the public about global climate change'.

Indeed.

What I especially liked about Dr Stewart's talk was his demonstration of the use of evidence from multiple disciplines, proving yet again that divisions between areas of knowledge are, and always have been, false. At the OU and in universities throughout the world scientists have an 'obligation' matched by, from what I have experienced, a fervent desire, to do just that. There is no doubt in my mind that it will be a long, hard campaign; but equally, hearing the public presentations in all media presented by scientists from UK and other universities throughout the world, I am convinced that we are not shirking our responsibilities.

Thank you all for your patience through a trying year for the *OUGSJ*.

And belated Happy New Year to you all.

— David M. Jones, *OUGS Journal* Editor

OUGS Geoff Brown Memorial Lecture — 25 April 2010: The Icelandic Eyjafjallajökull Eruptions 2010

Dr Dave McGarvie (Science Staff Tutor, the OU in Scotland and the OU in Yorkshire)

Author's note

During the final fettling of this paper in October 2010 the Eyjafjallajökull eruption was officially declared as 'over' by the Icelandic authorities, some four months after juvenile material last erupted from the summit crater. Perhaps surprisingly there have been no review papers or informed summaries of the eruption in the intervening months, but this is simply because scientists are busy working on the huge amounts of data that have been collected — and they are keeping quiet about their discoveries until they are ready to publish! But expect a flurry of informative and insightful papers to appear during 2011. And don't be surprised if some of the provisional information and interpretations presented in this paper on the Eyjafjallajökull eruptions are shown to be incorrect.

Introduction

About five years ago I gave the Geoff Brown Memorial lecture with the title 'Volcanic Eruptions into Iceland's Glaciers'. At the time this was an esoteric research area of interest to just a few poorly-funded enthusiasts such as myself. And although those of us working on volcano-ice interactions (also known as glaciovolcanism) knew full well that some ice-capped Icelandic volcanoes — especially those with ice-filled calderas/craters — could generate lots of fine ash, it is fair to say that Eyjafjallajökull found a way of producing a much higher proportion of fine ash than anyone anticipated.

In this talk I will cover the following:

- a hot-off-the-press overview of the ongoing summit eruption of Eyjafjallajökull, which started on 14 April 2010, and summary of the basaltic flank eruption that started on 20 March 2010 and ended just before the summit eruption began;
- my own research on the ice-capped Öraefajökull stratovolcano in south-east Iceland;
- my return to the Askja volcano in Iceland after a gap of 22 years — the last time I was there was in 1988 with Geoff Brown on one of his Earthwatch expeditions.

Eyjafjallajökull

Known by most non-Icelanders during the eruption as 'the Icelandic volcano' because they found it tricky to pronounce. Eyjafjallajökull (Fig. 1) means 'The glacier on the mountains next to the islands' and it is pronounced 'A-yah-fyaddla-yoekuddl'. Interestingly, it has the nickname of 'the quiet one' by some Icelanders on account of it being one of the least-active volcanoes in Iceland. This nickname is likely to disappear because of the two eruptions that took place in 2010 — the small basaltic flank eruption that started on 12 March 2010 and the summit eruption of intermediate magma (trachyandesite) that started on 14 April 2010.

It is important to note that the 2010 eruptions were the culmination of years of unrest at the volcano, with two distinct episodes of magma intrusion (interpreted as sills) recorded in

Figure 1 Eyjafjallajökull — as it looked in November 2009 (© Dave McGarvie).

© OUGS ISSN 0143-9472

1994 and 1999. How these intrusions either affected or influenced what was erupted in 2010 has yet to be evaluated, but it is likely that they played a key role in facilitating the uprise of magma in both of the 2010 eruptions, either by opening melt pathways in the crust, or by storing melt that subsequently became mobilised during the eruptions.

One fortuitous aspect of Eyjafjallajökull's recent unrest and eruptions is that because of its proximity to the neighbouring Katla volcano — which is intensively monitored — Icelandic scientists were able to gather excellent information on key parameters such as ground deformation and seismicity at Eyjafjallajökull. This has two important implications: first is that during the 2010 eruptions it was possible to discern links between what was going on at depth and what was happening at the eruption site(s); and secondly is that when the full story of the eruption is eventually published, it may prove to be a classic case study showing how the integration of volcanological and geophysical information can provide insight into the initiation, progress and ending of an eruption. It could in fact be pivotal in improving how Icelandic (and other) volcanoes are monitored in future.

In the months prior to the March flank eruption, there was a steady but persistent number of earthquakes beneath the volcano (Fig. 2), which were mostly located just east of the ice-filled summit crater. Magma was on the move. At the time it was suspected that this may result in another intrusion (as happened in 1994 and 1999), but the frequency, magnitude and location of the earthquakes did suggest that something more interesting was underway. And so it proved to be, with the uprising magma appearing to migrate or jink eastwards to break to the surface in the pass of Fimmvörðuháls, which is the low and relatively ice-free col between Eyjafjallajökull and Katla. Fimmvörðuháls can be roughly translated as 'pass of the five cairns'. A basalt eruption started on 12 March 2010 (Fig. 3). This was a typical small Icelandic fissure eruption, with Strombolian activity producing modest fire fountains and lava flows. It was what Icelanders term an excellent 'tourist' eruption, with access being relatively easy, and with little danger of anything either dangerous or unexpected happening. It encouraged many tourists to fly to Iceland. Nights were especially popular, as the glowing lava within the slowly progressing flow fronts could be seen to best effect, plus the glow of the pulsating fire fountains was spectacular. On some nights the Northern Lights appeared, adding extra drama and colour to already unforgettable memories. So far so good.

Figure 2 The locations of earthquakes at Eyjafjallajökull both from above and in a cross section through the crust. The colour code gives the time sequence of the earthquakes, with black and red being the most recent (Courtesy of the Institute of Earth Sciences, University of Iceland).

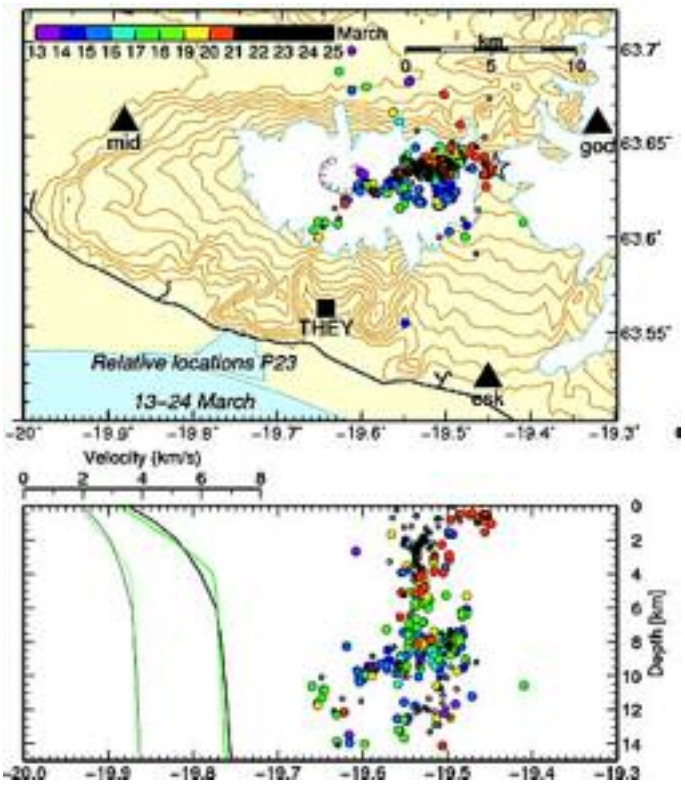


Figure 3 Eyjafjallajökull flank eruption. Basaltic fire fountains, scoria cone and lava flow advancing through and over snow at the March 2010 fissure (Courtesy of Guðrún Sverrisdóttir).

Of particular interest to me (from a volcano-ice perspective) was the way in which the lavas were carving narrow channels into the ice and firn, with steam plumes indicating intense (but not explosive) lava-ice interactions (Fig. 4, *opposite, top*). It would have been great to have been out there observing these and comparing the features produced during real-time lava quenching with the quench features in pre-historic lavas that I have been working on elsewhere in Iceland (*see* Fig. 18), but I simply could not take the time off. I was very conscious that the lava streams were heading towards a cliff, and I could only hope that the eruption would continue until the lavas reached the cliff edge. Fortunately the eruption continued, and the cliffs were reached.

When the lavas reached the cliffs we were treated to what I regarded as two especially spectacular types of eruptive activity. The first was what some people called a 'lava waterfall', which conveys an impression of the phenomenon well, but of course is an odd term to use (Fig. 5, *opposite, bottom left*). The second was when some lavas flowing in the steep ice- and snow-filled gullies below the cliffs trapped either snow/ice or meltwater. As the meltwater and steam could not escape freely this resulted in intense and episodic explosions (Fig. 6, *opposite, bottom right*). The explosions were fuelled by steam formation, because at atmospheric pressure the conversion of water to steam involves about a thousand times expansion in volume. If some of the energy of this steam formation contributes to lava fragmentation, then you can expose more hot lava to more meltwater, and thus you can get a form of fuel-coolant (chain) reaction limited only by the availability of coolant (meltwater) and fuel (molten lava). At the time nobody thought this was more than a spectacular and

Figure 4 Eyjafjallajökull flank eruption. Intense steam rising from the margins of lava flows that steadily melted their way through snow and firn/ice (Courtesy of Magnús Tumi Guðmundsson).

localised example of lava-water interaction. In hindsight it was a foretaste of the more extensive and explosive interactions at the summit eruption that was yet to happen. Finally, from an instructive perspective, the episodic explosions in the gullies where water was trapped contrasted neatly with the gentle and steady steam plumes associated with the narrow lava channels emanating from the vent areas (Fig. 4), where the meltwater and steam was free to escape.

Activity at the Fimmvörðuháls vents diminished markedly and on 12 April 2010 the flow of magma to these vents stopped while at the same time eruption (seismic) tremor reached a minimum, indicating that little or no magma was moving up the conduit towards the vents. The 'tourist eruption' was coming to an end. By this time I had already started making plans to visit the gullies and the lava channels in June with one of my PhD students and her supervisors, as by then things would have stabilised and cooled down sufficiently to enable us to make detailed measurements of cooling fractures and lava morphologies. These plans were scuppered by what happened next.

On 13 April 2010, just one day after activity at the Fimmvörðuháls basalt vents ceased, there was an intense seismic swarm beneath the summit area of Eyjafjallajökull (Fig. 7, *overleaf*). This was rather unexpected, as it was reasonable to assume that any build-up of pressure (and magma) within the sub-volcanic plumbing system had been released during the Fimmvörðuháls flank eruption. On 14 April 2010 an eruption at the summit was confirmed. At the time it was not known what the magma composition was, but most people reasonably assumed that as it had been basalt that was being erupted near by at Fimmvörðuháls, that it was basalt that was also being erupted at the summit. However, there were early indications (colour of eruption plume, higher than expected degree of fragmentation — even allowing for the presence of ice in the summit crater — that there was something unusual about the magma that was being erupted (Fig. 8, *overleaf*). This was confirmed when the first analyses showed that the magma was intermediate in composition with an SiO_2 wt% of *c.* 57–60%. This SiO_2 range is typical of andesites (57–63 wt% SiO_2), but because the Eyjafjallajökull magma is richer in alkalis (Na_2O and K_2O) it is more accurately classified as a trachyandesite. Iceland is a dominantly bimodal volcanic island, dominated by basalts (*c.* 90%) and rhyolites (*c.* 10%), with intermediate compositions being fairly uncommon. However, the volcanoes of the Icelandic flank zones (so called because they lie on the flanks of the main zones of active rifting and spreading) tend to produce a higher proportion of rhyolites (Fig. 9, *overleaf*) and, more importantly, they also produce a higher proportion of intermediate compositions. Without getting into petrological detail, Icelandic flank zone volcanoes tend to be larger and longer-lived than their counterparts in the active rift zones, but they also produce magmas that are richer in alkalis — hence the trachyandesite that was erupted from the summit of Eyjafjallajökull in April–June 2010. This composition did surprise some geologists, but it did not surprise those of us who work on Icelandic volcanoes and their eruptive products. As to the origin of the trachyandesite, this is still not known, but will be revealed when the papers are published.

Figure 5 Eyjafjallajökull flank eruption. Basalt lava falling over the cliffs to the North of the vents. The Icelandic scientist in the image is Professor Magnús Tumi Guðmundsson of the University of Iceland, whose PhD thesis was examined by Professor Geoff Brown of The Open University (Courtesy of Magnús Tumi Guðmundsson).

Figure 6 Eyjafjallajökull flank eruption. Steam explosions as a basalt lava encounters ice within a steep-sided gully. Darker patches within the cloud show that it is not just steam being generated, but that explosions are also pulverising and fragmenting some of the lava (Courtesy of Guðrún Sverrisdóttir).

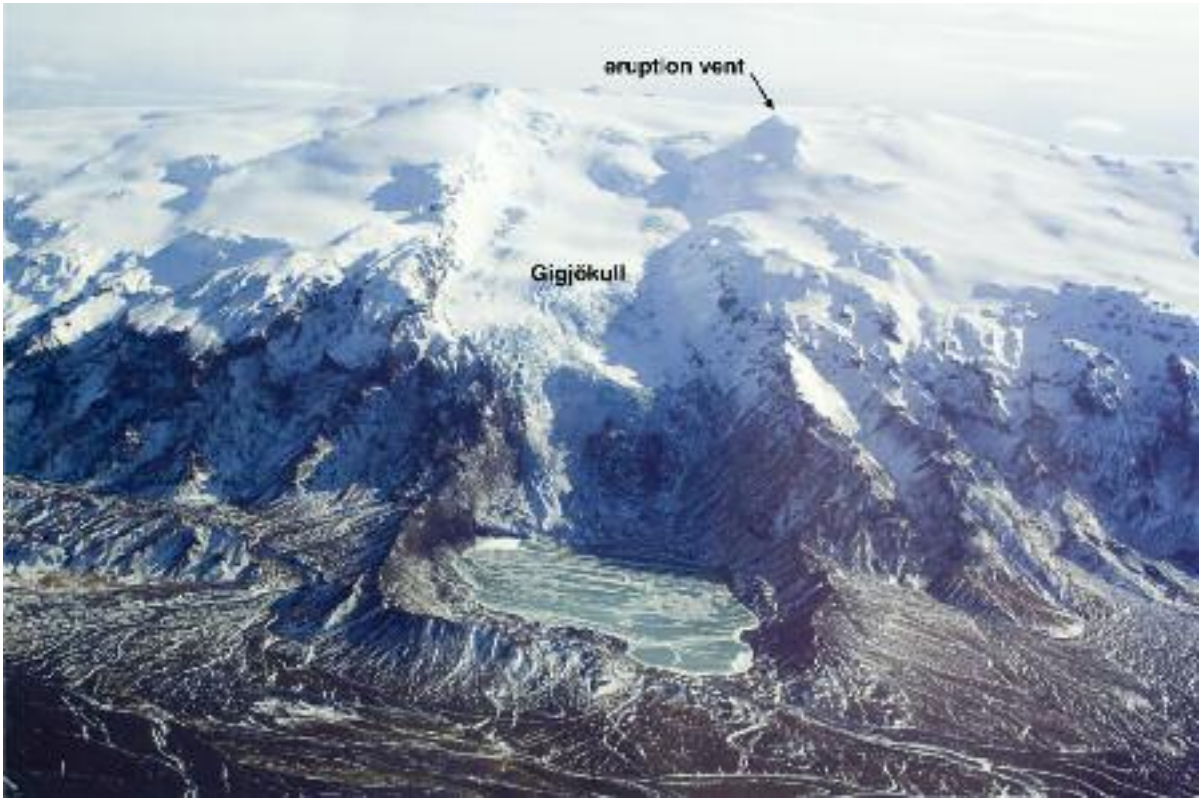


Figure 7 Eyjafjallajökull before the summit eruption of 14 April 2010. 'Eruption vent' shows the site of the eruption, and Gigjökull is the valley glacier that emanates from a breach in the summit crater, and down which there was a large flood early in the eruption (Courtesy of Finnur Pálsson).

There are two simple mechanisms for producing trachyandesite magma: the first is that it is the product of fractional crystallisation from a basaltic parental magma of alkaline affinity; and the second is that it is a 'hybrid' magma generated during mechanical mixing of a mafic (e.g. basaltic) end-member magma and a silicic (e.g. rhyolitic) end-member. Of course both of these mechanisms could be involved. A personal communication from an Icelandic colleague revealed that highly forsteritic (i.e. Mg-rich) olivine crystals had been found within the trachyandesite tephra close to the summit vent. This may add weight to the hybrid magma mechanism, as such Mg-rich olivines would be in equilibrium with basaltic magma but most definitely not with trachyandesite magma. Consequently these olivines would have been derived from the basaltic end-member. However, there are

Figure 8 Eyjafjallajökull summit eruption on 16 April 2010 (Courtesy of Marco Fulle).

Figure 9 Rhyolites at one of the flank zone volcanoes — Torfajökull. Older rhyolites are distinctive by their yellowish colours. The dark and fresh looking lavas are young rhyolite lava flows erupted in 1477 AD (© Dave McGarvie).

other ways of getting Mg-rich olivines into a trachyandesite magma (e.g. blasting apart a pre-existing poorly-consolidated olivine-rich tuff), so until full details have been published we should keep an open mind about what mechanism produced the trachyandesite. It may even turn out that mechanisms other than fractionation and magma mixing were involved. There is surely a fascinating story underlying the trachyandesite magma that was erupted from April–June 2010 at Eyjafjallajökull's summit.

But of course it was the more widespread ramifications of the Eyjafjallajökull summit eruption that was of interest to the wider world, as it caught Europe completely unprepared for such an event and led to the closure of airspace and massive disruption to air travel. Despite volcanologists warning politicians for decades that such an event might happen, the usual short-termism that pervades UK politics meant that politicians chose to ignore the potential hazard and so no effective advance planning had taken place. Of course the summit eruption of Eyjafjallajökull was a study in 'perfection' with respect to creating havoc across European airspace, because there was a perfect conjoining of three crucial factors: first, the prevailing wind was in the right direction (i.e. direct from Iceland to the UK, because the jet-stream was over Iceland at the time); second, the eruption produced an unusually high proportion of fine ash (i.e. capable of being transported long distances), most of which stayed in the lower atmosphere (Fig. 10); and third, we had a stable high pressure system with us at the time (i.e. we did not have the usual stream of rain-laden depressions washing the ash out of the sky).

The exact reasons behind the production of such a high proportion of fine ash in this eruption are not known, but the main contributing factors are likely to include:

1. Magma viscosity: trachyandesite has a higher viscosity than basalt, and so escaping volatiles have a greater tendency to fragment the magma rather than to stream through it and escape more readily. This is why explosive degassing during basalt eruptions tends to produce fire fountains whereas explosive degassing of andesitic-rhyolitic eruptions tends to produce eruption columns.
2. Volatile content: more evolved magmas tend to have higher concentrations of volatiles simply because there is no place for the volatiles to go within the lattices of any common minerals that may form. Consequently the volatiles remain with the remaining melt fraction and hence are found in higher concentrations within evolved magmas. Therefore rhyolites will tend to have higher volatile contents than basalts, leading to enhanced explosivity.

   Furthermore, as volatiles tend to be concentrated towards the top of a magma body, the first-erupted magma tends to tap the top first and hence it is usually the most explosive part of the eruption. Lava flows are usually produced later in the eruption as volatile concentrations diminish, during non-explosive degassing (Fig. 11).
3. Ice: in perfect heat transfer conditions trachyandesitic magma can melt about eight times its own volume of ice. When this meltwater is flashed to steam (again under perfect surface atmospheric conditions) there is a c. 1,000 times expansion in volume. So one unit of trachyandesite magma has the potential to produce 8,000 units of steam. In reality it will be less than this, but the key point is that the energy liberated during steam expansion can in turn be used to fragment further magma. And if this is magma already has a tendency to erupt explosively and fragment due to its higher viscosity and higher volatile contents, then the presence of ice provides additional fragmentation energy. It is likely that without the presence of ice during this eruption (i.e. within the ice-filled summit crater), this eruption would not have been so problematic for the UK and Europe, simply because it would not have produced the high volumes of fine ash at sufficiently high and

Figure 10 Eyjafjallajökull summit eruption. Showing large amounts of fine-grained ash being ejected from the vent (capture from Vodaphone webcam on Þórólfsfell).

Figure 11 An example of a rhyolitic lava flow and thick pile of ash erupted during the same eruption (Hrafntinnusker, Torfajökull volcano). The ash was erupted during an early explosive degassing phase, and the lavas effused during a later non-explosive degassing phase. The person on image to the left, just below the snow, is 1.80m tall. (© Dave McGarvie).

Figure 12 Eyjafjallajökull summit eruption. Spectacular image taken at night (Courtesy of Marco Fulle).

Figure 13 In the pathway of the flood that thundered down the Gigjökull Valley glacier on 14 April 2010 at the start of the Eyjafjallajökull summit eruption. At the time the photo was taken (23 June) the eruption was nearly over with only small ash bursts in the summit crater (author provides a scale; © Dave McGarvie).

persistent rates. The papers that will eventually appear in the scientific literature will no doubt say a great deal more about this particular aspect of the eruption.

The aftermath rumbles on, and it has been a fascinating and long-overdue wake-up call for Europe, and for the UK in particular, that while we live on a relatively stable piece of crust, we are not immune from the effects of volcanic eruptions originating from our fish-rich neighbour to the north-west. But ignoring this and getting back to the eruption itself, it has to be said that many of the images of the eruption were truly spectacular (Fig. 12), and some of the video footage was inspiring. I have said it a number of times and I will repeat it here — we will learn a great deal from this eruption.

The final comment I wish to make about this eruption is how well prepared the Icelanders. This is due largely to a population that accepts that eruptions and earthquakes happen where they live, as their parents and grandparents will have told sagas and tales of their own experiences. I recall babysitting the five-year-old daughter of some Icelandic friends in their third-floor apartment when the building shook violently for a few seconds. A bit shaken but quite invigorated I looked over to the daughter and asked her in my poor Icelandic if that was an earthquake. She looked up, smiled and said yes, and continued her crayoning without a pause. With respect to the 2010 summit Eyjafjallajökull eruption the Icelanders had already anticipated such a scenario (and many others) and so they had an evacuation plan, which was prepared a few years ago, that was implemented swiftly when the strong possibility of a flood appeared likely (Fig. 13), because it has long been known that it is the floods (jökulhlaups) that are the main hazards from Icelandic ice-capped volcanoes. Nobody was killed or injured. The evacuation plan worked a treat.

Öraefajökull

The upper half of this *c*. 2km high stratovolcano is covered with ice and at the summit is an oval 3–5km diameter caldera up to 500m deep (Fig. 14), which is filled with ice. On the rim of this caldera stands Iceland's highest point at 2,110m, which is rhyolite. This is rather pleasing as rhyolite is the main rock type I work on. Öraefajökull has had two historic eruptions (i.e. in the *c*. 1,100 years since Iceland was settled by Nordic peoples): a modest basaltic andesite eruption in 1727, which nevertheless

Figure 14 Öraefajökull. Aerial view of the ice-covered upper half of the stratovolcano. The smooth oval shape is the ice-filled, c. *5km × 3km, summit caldera. Figure 17 shows part of the ice-free lower flanks (Courtesy of Jack McGarvie).*

Figure 15 left, Evidence of pyroclastic flows within an archaeological dig on the lower flanks of Öraefajökull; right, Evidence of pyroclastic flows (cross stratification) at 800m elevation (© Dave McGarvie).

triggered devastating and life-taking floods; and a larger rhyolite eruption in 1362, which remains Iceland's most explosive silicic eruption of the historical period. There are no eye-witness accounts of the 1362 eruption, and this may be because either the inhabitants of this highly-prosperous land paid heed to the earthquakes that preceded the eruption and had the good sense to evacuate, and/or that those who remained were killed by pyroclastic flows that occurred early in the eruption. These pyroclastic flows were only 'discovered' a few years ago when Icelandic archaeologists (Fig. 15), in excavating a farm site affected by the eruption, exposed a sufficiently long trench in which the subtle structures characteristic of distal pyroclastic flows could clearly be seen by visiting Icelandic volcanologists. Of the 1727 eruption there is better first-hand information, including an excellent eye-witness account by Jón Þorláksson (vicar) that describes the earthquake activity prior to the eruption, the floods, the eruption itself and the human suffering. Two brief quotations illustrate these:

> "In the year 1727, on the 7th August, as I stood before the altar, I was conscious of a gentle concussion under my feet … [which] continued to increase and alarm the whole congregation. One of them, a very aged man, went to a spring … where he prostrated himself … and said 'Be on your guard, Sir, the earth is on fire!"
> "Two women and a boy took refuge on the roof … but it was carried away by the deluge of water, and as far as the eye could reach, the three unfortunate persons were seen clinging to the roof. One of the women was afterwards found among the mud of the jökulhlaup, but burnt, and as it were parboild; her body was so damaged and tender but it could scarcely be touched."

Figure 16 Rhyolite outcrops on the lower flanks of Öraefajökull. The large buttress is composed entirely of columnar-jointed rhyolite — the remnants of a rhyolitic lava that flowed when ice completely occupied the space between the photographer and the buttress. The base of the flow forms a prominent dark line above grey scree. The more vegetated units below the rhyolite comprise various debris flows, tillites, and mafic lavas (© Dave McGarvie).

Figure 17 Part of the lower flanks of Öraefajökull and the results of mapping them (inset) (© Dave McGarvie).

Of particular interest to my research is that there are extensive outcrops of rhyolite within the lower ice-free half of the stratovolcano (Fig. 16, *previous page*). These are being studied through two projects. The first involves mapping one of these areas to reconstruct the geological history of the lower flanks of the stratovolcano (Fig. 17). Mapping is being combined with geochemistry to enable individual magma batches to be identified (as each has a subtle but unique fingerprint), and with Ar-Ar dating to enable us to understand the time taken for the volcano to grow and how magma compositions have changed through time — as well as getting an estimate of the rate of magma production, which may help us understand hazards from future rhyolite eruptions. Another project is examining interactions between rhyolite lavas and ice. And we are fortunate also to have some trachyandesite and trachydacite lavas that have also interacted with ice (Fig. 18), because while these possess some cooling fractures that are similar to those in rhyolites, others are quite different, which suggests that the intrinsic physical characteristics of lavas (e.g. viscosities, available thermal energy) exert an important control on the type and abundance of cooling fractures that are developed when lavas encounter ice and snow.

Figure 18 Trachyandesite lava that flowed down a snow-filled gully at Öraefajökull. The prominent fractures (that look like curving millipedes) are called 'pseudopillow' fractures as they often connect to enclose vaguely pillow-like shapes (Ó Dave McGarvie).

The main purpose of briefly mentioning Öraefajökull is that this is another Icelandic volcano that has the potential to erupt explosively and, conditions permitting, affect transatlantic air travel for a period lasting from a few days to a few weeks (Fig. 19, *opposite, top*). Given that the 1362 eruption almost certainly injected a considerable amount of ash into the stratosphere, a similar eruption today would have longer-term effects, as ash in the stratosphere has a longer residence time and this is also where commercial jet aircraft fly because of fuel efficiency requirements. Note that this scenario is unlike the 2010 summit eruption of Eyjafjallajökull, where most of the ash stayed in the troposphere.

Askja

Askja is a spectacular volcano in the uninhabited interior of Iceland. Within a doughnut-shaped ring of brownish basalt produced during eruptions into ice lies the blue jewel that is the 420m deep and 5km diameter lake that fills the caldera created in the aftermath of Askja's 1875 rhyolite and basalt eruption (Fig. 20, *opposite, bottom*). I last visited Askja in 1988 with Geoff Brown, and as mentioned at the last Memorial Lecture I gave, memories of my times at Askja with Geoff were fundamental

Figure 19 Large rhyolite pumice bombs from the 1362 eruption of Öraefajökull (© Dave McGarvie).

in stimulating me into undertaking the first detailed research projects on rhyolite eruptions into ice.

Interestingly, an important phase of the 1875 eruption of Askja involved the highly-explosive eruption of rhyolite, which produced a Plinian eruption column (Fig. 21, *overleaf, top*). There was much ashfall in the east of Iceland, and were this eruption to occur today it is likely that transatlantic air travel would be seriously disrupted.

I briefly mention Askja because I am involved in a research grant (funded by the National Science Foundation in the U.S.A.) to undertake the first detailed study of how Askja has grown and evolved during past glacial periods. At the time of the lecture I was simply planning my trip to Askja in late July but at the time of writing (October) I have had a successful trip and would like to take this opportunity to report briefly on just two aspects of our work and to include some new images. The first aspect is that while we have found much that is complex and new, there is an apparent underlying simplicity in that the eastern massif of Askja in which we were working is composed of sheets and mounds of pillow lavas that are closely associated with variably deformed piles of fragmental basalt that we currently assume to be cogenetic (i.e. erupted during the same event that erupted the pillows) (Fig. 22, *overleaf, bottom, left*). Labwork is being undertaken to test this assumption. The second aspect is that there is a plethora of interesting intrusions of various shapes and sizes, which have variable interactions with their intruded hosts (Fig. 23, *overleaf, bottom, right*). So there is plenty to engage the interest, and plenty of puzzles to solve over the next few years.

Conclusion

At the time of giving the lecture in April the 2010 the summit eruption of Eyjafjallajökull was ongoing, and we were faced with considerable uncertainty over the future development of the eruption. It has brought home to us in the UK that we are not immune from volcanic hazards, despite having no active volcanoes within our bounds. The volcanoes of Öraefajökull

Figure 20 Askja. The lake that formed after the 1875 eruption. Interestingly there is a mismatch between the volume of the depression and the volume of the magma erupted at Askja, which has led some geologists to suggest that the 'missing mass' can be explained by basalt lava eruptions and dyke intrusions that occurred to the north, the interpretation being that the basalt magma was underneath Askja but moved laterally to the north in fissures (© Dave McGarvie).

Figure 21 Askja. The pale coloured material covering much of the landscape is rhyolitic pumice and ash from the 1875 eruption (© Dave McGarvie).

and Askja have both produced highly explosive eruptions during the historical period (the past *c*. 1,100 years), and had these eruptions occurred today they would cause considerable disruption to air travel, albeit different in some ways from the disruption experienced during the 2010 summit eruption of Eyjafjallajökull. These volcanoes will erupt again, and some of their eruptions will be highly explosive ash-forming ones, though it should be emphasised that the geological record shows that such highly explosive eruptions are quite rare even at these volcanoes. My research at Öraefajökull and Askja is focused not on the scanty proximal remnants of their infrequent, highly explosive eruptions, but instead on the volumetrically-dominant lavas and volcaniclastic deposits of these volcanoes as these will yield more and better information on the growth and evolution of Icelandic central volcanoes. At Öraefajökull I am contributing to a project that aims to reconstruct the lower (exposed and ice-free) flanks of the volcano, and at Askja I am contributing to a project that is attempting the difficult task of reconstructing the growth and evolution of the volcanic during past glacial periods. In summary, there is enough research to keep me going back to Iceland for a few more happy years, for which I am grateful.

Figure 22 Askja. Pillow lavas (© Dave McGarvie).

Figure 23 Askja. A dyke intrusion; scale is 1m long. (© Dave McGarvie).

Paleogene volcanism and sedimentation in the Faroe Islands

Duncan Woodcock

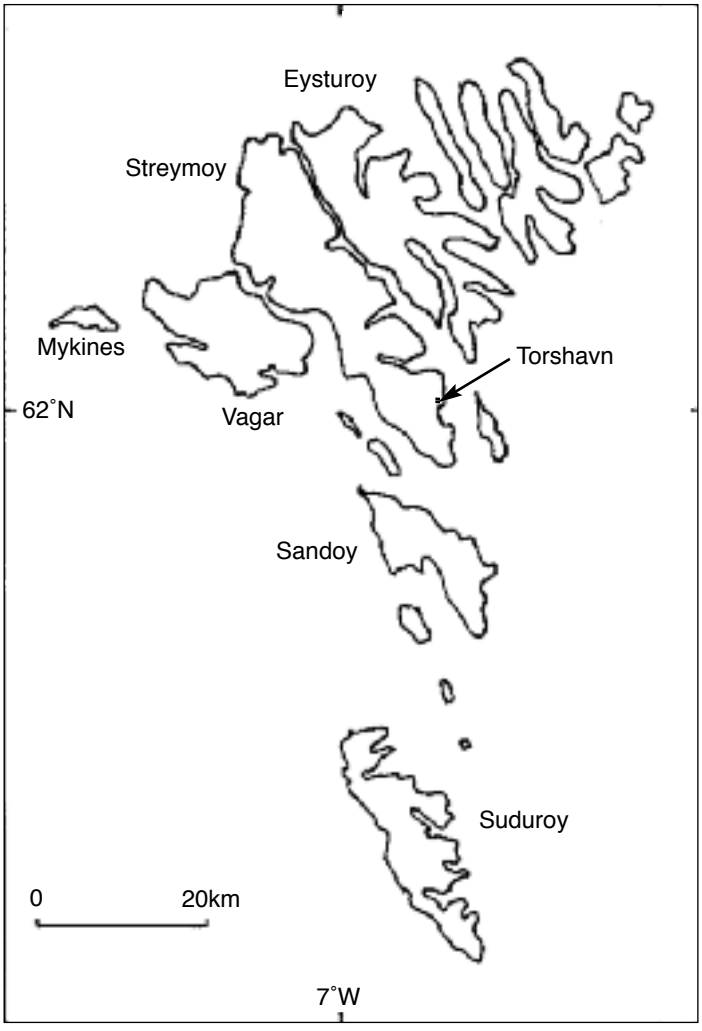
Introduction

The Faroe Islands lie at 62˚ N in the NE Atlantic Ocean between Shetland and Iceland. Today they seem remote, yet in Viking times they were at the centre of a trading area that stretched from Norway to Greenland. The archipelago of 18 islands (Fig. 1) is sparsely populated, with about half of the total population of 50,000 settled in the capital, Torshavn, on the island of Streymoy. The daily flight by Atlantic Airways from Copenhagen lands at the small airport on Vagar that was built during the brief Allied occupation of the islands during WW2. If visibility is good, the flight provides a splendid aerial introduction to the geology (e.g. Fig. 3).

The islands, along with the surrounding shelf, comprise the Faroes Platform — a remnant of a more extensive Paleogene flood basalt province known as the North Atlantic Igneous Province. Post-eruptional tilting of the archipelago, together with extensive Quaternary glaciation, exposes for examination of an onshore cumulative thickness of basalt in excess of three kilometres.

This note is based on an eight-day visit to the Faroes in August 2008. The excursion was organised by Simon Passey of the Faroese Earth and Energy Directorate and run immediately after the 33rd International Geological Congress in Oslo. Generous support of the excursion by StatoilHydro enabled us to travel extensively and in particular to examine some of the relatively inaccessible sea cliff exposures from the relative comfort of the charter vessel *Vanir*.

Figure 1 Location map of the Faroe Islands.



History of geological research

Geological fieldwork in the Faroes dates back to the 19th century, culminating in a visit by Archibald Geikie, who sailed round the area in his yacht and published an account of his travels.

The heyday of Faroese geological fieldwork was the period 1930–1969, when Johannes Rasmussen and his supervisor Arne Noe-Nygaard carried out a systematic programme to map the whole archipelago. This was an outstanding achievement, carried out on foot and from a rowing boat before the development of the modern road and ferry network. Their work culminated in the publication of a geological memoir (Rasmussen and Noe-Nygaard 1970), which remains to this day the definitive work on Faroese geology.

More recent work has tended to concentrate on the geochemistry of the basalts (Waagstein 1988). An important exception to this trend was the work undertaken by Simon Passey for his PhD (Passey 2004) and subsequent publication (Passey and Bell 2007); this work comprises the first modern volcanological study of the Faroe Islands basalts and interbasaltic sediments.

Stratigraphy of the Faroe Islands Basalt Group (FIBG)

Figure 2 *(overleaf, top)* shows a schematic of the stratigraphy of the FIBG. A total thickness of more than 3km can be observed subaerially, with a further 3.5km penetrated in a borehole. The onshore FIBG is divided into three main formations — the Beinisvord, Malinstindur and Enni Formations — each with its own distinctive geochemistry and style of volcanism. These formations are separated by major volcanic hiatuses and periods of sedimentation. This paper seeks to focus on the physical volcanology of the lavas and interbasaltic sediments; for geochemical and petrological details of the lavas the interested reader should refer to the literature (Waagstein 1988 and others).

Physical volcanology of the FIBG

As a preliminary, we define a flow lobe as the fundamental unit of a lava flow, comprising an individual package of lava surrounded by a chilled crust. A lava flow can comprise one or more flow lobes, with individual lava flows typically separated by weathering surfaces of sediments. A simple lava flow comprises a single flow lobe; a compound lava flow contains two or more lobes (Walker 1972). Figure 3 *(overleaf, bottom)* shows the typical 'trap' topography that develops within a series of simple lava flows. Figure 4 *(page 13, top left)* shows the contrast between the simple flows of the Beinisvord Formation and the compound flows of the overlying Malinstindur Formation.

The extensive sheet flows that comprise the FIBG were originally considered to be rapidly emplaced aa flows. More detailed studies have cast doubt on this interpretation. The flows do not have rubbly bases, except locally where brecciation was produced by contact with wet sediments. Furthermore, the 'rubbly tops' that were cited as evidence of an aa origin can be shown to comprise the weathered vesicular tops of pahoehoe flows.

© OUGS ISSN 0143-9472

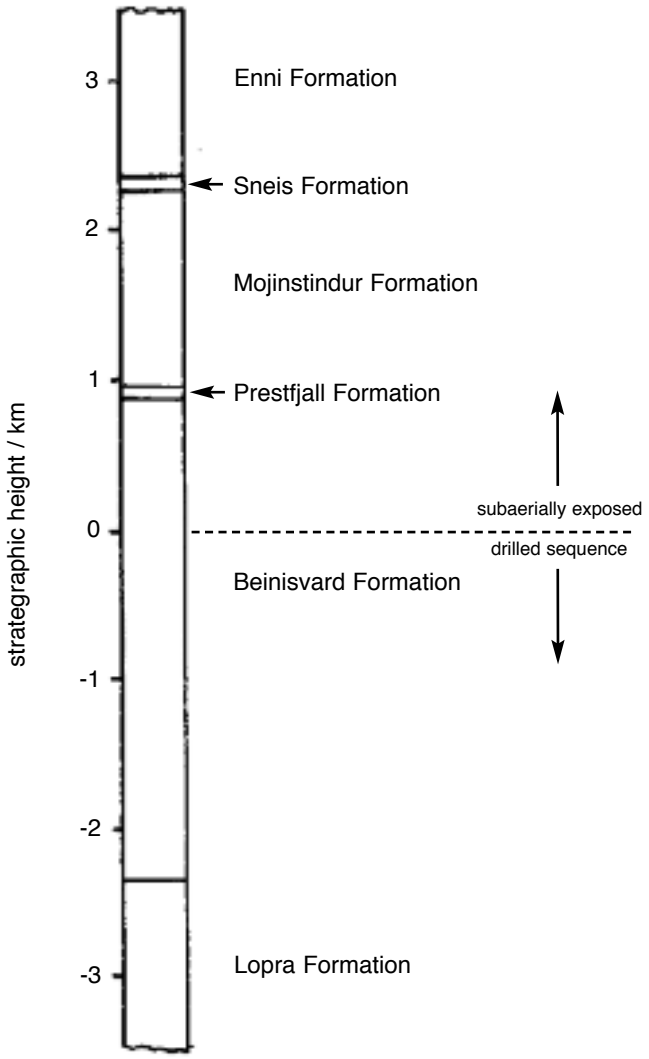


Figure 2 Stratigraphy of the Faroe Islands Basaltic Group (FIBG) (from Passey and Bell 2007).

The flows of the FIBG are currently considered to be large pahoehoe flows that were emplaced by inflation (Self *et al.* 1998). Inflation envisages the initial emplacement of relatively thin flow lobes that are progressively thickened as additional lava is 'pumped' into the molten core of the lobe contained within a progressively thickening crust.

Surface features of lava flows are poorly displayed on the Faroes; during the trip we saw only two poorly preserved ropy pahoehoe surfaces. In contrast, the combination of glacial and marine erosion has produced excellent exposures of the internal structures of the lava flows.

Figure 5 *(opposite, bottom left)* shows a section through a typical flow lobe within a compound lava flow of the Malinstindur Formation. The lobe has a vesicular top, a massive core and a vesicular base containing elongate pipe amygdales (vesicles infilled with minerals — in this case zeolites). In this example the vesicular top has a thickness of about half of the total lobe thickness and contains a uniform distribution of small, sub-spherical amygdales.

A close-up view of some pipe amygdales is presented in Figure 6 *(opposite, top right)*. The origin of pipe vesicles has been a source of controversy in the geological literature (Walker 1986; Godinot 1986; Phillpots and Lewis 1986). The volatiles that produce the vesicles were originally thought to be sourced from the underlying substrate; however, examination of Figure 6 shows that there is a gap between the base of the pipe vesicles and the base of the flow. This gap, together with the observation that pipe vesicles can occur in each lobe within a compound lava flow, suggests that the vesicle-forming volatiles are more likely to have a magmatic origin.

Additional controversy arose over whether a pipe vesicle represented the trace of a rising bubble. The presence of radially orientated pipe vesicles in some pillow lavas (and in ice cubes produced in the freezer!) indicates that the mechanism for formation must be independent of gravity. The tip of the inward-growing pipe vesicle is thought to track the position of a 'solidification front' that separates material below with a significant yield strength from material above that has a much lower yield strength. Crystallisation of anhydrous minerals at this solidification front causes volatiles to be exsolved by retrograde boiling, with the bubble preferentially developing into the weaker material above the solidification front. The trace of the growing bubble is preserved below the solidification front as an open 'pipe' because the yield strength of the material is sufficient to prevent closure behind the bubble. The progressive decrease in speed of the solidification front limits the length of the pipe vesicles: if the front moves too slowly, the bubble at the top of the pipe breaks away. Finally, pipe vesicles are often inclined in the direction of the lava flow, thus providing good indication of local paleoflow direction.

Figure 3 Trap topography developed in a series of simple lava flows, west end of Mykines, Faroe, Islands (© Duncan Woodcock).

Figure 4 Cliff section at Soydistangi viewpoint, Eysturoy, Faroe Islands. This spectacular locality shows the contrast between the simple flows of the Beinisvord Formation and the overlying compound flows of the Malinstindur Formation (© Duncan Woodcock).

The solidification front concept can also be used to explain the distribution of vesicles in the upper vesicular zone of the flow lobe: they record the progressive downward movement of an 'upper solidification front'. Bubbles of exsolved volatiles are produced at the upper solidification front but are unable to rise into the high yield strength material above the upper solidification front. Most lobes display a uniform distribution of vesicles in the upper vesicular zone, suggesting continuous, steady inflation. However, some lobes show distinct layers of vesicles: these may be the result of unsteady inflation, with low rates of inflation corresponding to high vesicle concentration.

The vesicular top and base of a lobe enclose a generally massive central core. This core results from the solidification of the lava between the upper and lower solidification fronts at the time when inflation finally ceased. The core is generally free of vesicles, apart from widely spaced cylindrical vesicles with a

Figure 5 Section through a typical flow lobe in a compound lava flow, Stora, Eysturoy, Faroe Islands (© Duncan Woodcock).

Figure 6 Pipe vesicles in the lower vesicular zone of a typical flow lobe, Stora, Eysturoy, Faroe Islands. The vesicles are infilled with zeolite minerals (© Duncan Woodcock).

typical diameter of 20–50mm. Figure 7 shows a good example of these so-called segregation vesicles. These are quite distinct from the pipe vesicles below and have a different origin. They develop as a result of segregation of the final residual fluid phase resulting from progressive crystallisation of the basalt. This fluid is enriched in silica and thus less dense than the host basalt, consequently it tends to rise diapirically under the influence of gravity.

A final feature arising from the emplacement and growth of lava lobes by inflation is the presence of lava tubes. In order for the more distal portion of the lava lobe to grow by inflation, lava must be conveyed there from the source through the more proximal regions: this is most effectively conveyed via a progressively branching network of lava tubes. When inflation finally ceases, these tubes may drain to leave lava caves or the lava may solidify *in situ* to produce dense, massive cores of lava. Lava caves have not been reported in the Faroes — possibly because the flow field was erupted onto a near horizontal surface. Infilled lava tubes can often be seen in cliff exposures, such as the example shown in Figure 8 (*overleaf, top*). Occasionally, three-dimensional exposures occur on land, when the dense massive core has been stripped of its surrounding carapace of less resistant material by erosion (Fig. 9, *overleaf, bottom*).

Figure 7 Segregation vesicles (diameter c. *30mm) in the massive central core of a flow lobe — road cut at Ljosa, Eysturoy, Faroe Islands (© Duncan Woodcock).*

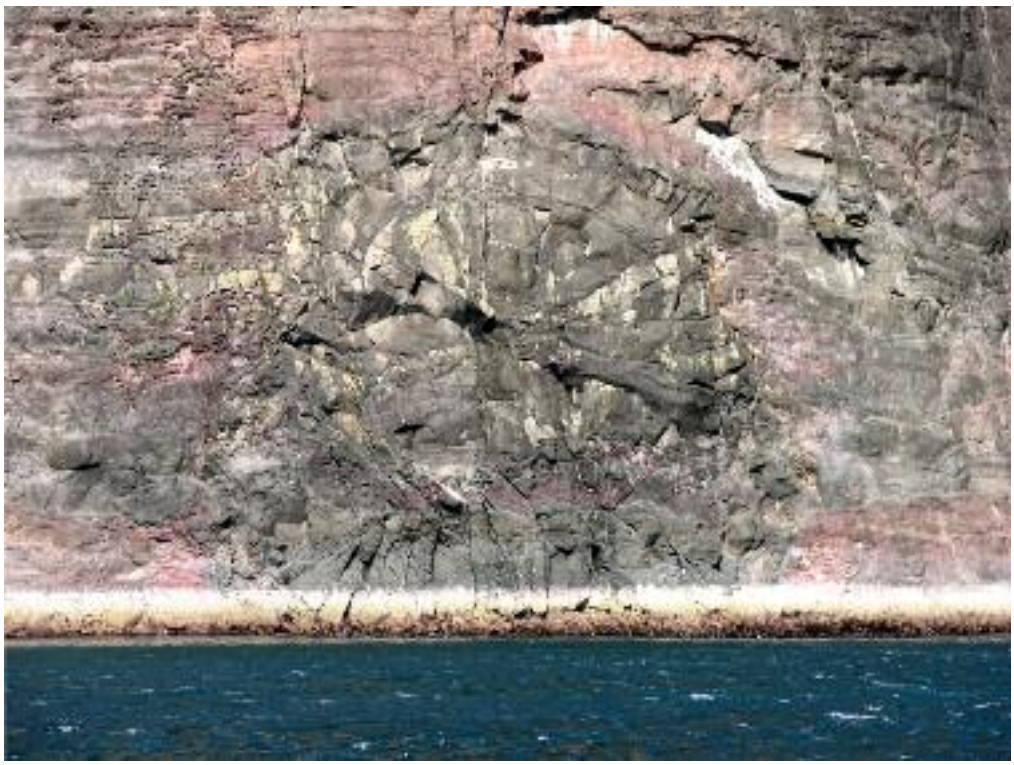


Figure 8 Infilled lava tube (diameter c. *5m) exposed in a cliff section, Vestmannaflogvi, Streymoy (© Duncan Woodcock).*

Many of the larger flows show well-developed columnar jointing. This well-known feature is caused by post-emplacement cooling, contraction and consequent tensional failure of the basalt sheet. The most regular columns form when regularly spaced isotherms can progress inwards towards the centre of the lobe during cooling (Fig. 10, *opposite, top*). The surfaces of columns are often marked by a series of horizontal marks stacked one above another: these are known as 'chisel marks' and demonstrate that the joint surfaces bounding the columns were formed discontinuously. Each chisel mark comprises a couplet: a relatively smooth surface caused by brittle fracture of the cooled lava followed by a rougher surface formed when the fracture 'overran' into the more ductile material.

The Interbasaltic sediments

Minor layers of interbasaltic sediments occur between most of the simple lava flows of the Beinisvord Formation. The presence of reddened soil horizons and the occasional tree mould attest to considerable periods of time between individual flows at any given location (Fig. 11, *opposite, bottom left*).

The three subaerial formations of the FIBG are separated by major periods of volcanic hiatus and sedimentation (*see* Fig. 2). The volcanic hiatus between the Beinisvord and Malinstindur Formations contains the Prestfjall Formation, which comprises sandstones and shales, as well as hosting a significant coal seam, which is mined locally on the island of Suduroy. Within the coal mine the seam is about one metre thick and contains a hard, shiny vitreous coal resembling anthracite: presumably the original lower-rank coal was thermally metamorphosed by the emplacement of the overlying Malinstindur Formation. The trip underground from the mine entrance to the coal face is along tunnels supported by wooden pit props and escorted by a miner with an acetylene lamp!

The volcanic hiatus between the Malinstindur Formation and the overlying Enni Formation is marked by the sandstones and conglomerates of the Sneis Formation. The sandstones are texturally and mineralogically immature: they comprise fragments of variably palagonised basaltic glass, together with plagioclase feldspar phenocrysts and basaltic rock fragments. Quartz is conspicuously absent from the material studied to date, suggesting a local provenance for the sediments.

A brief note on zeolites

The vesicles in the lava flows of the FIBG are almost always wholly or partially infilled with a variety of zeolites, so the vesicles are really amygdales. It would have been possible to spend the whole field trip just looking at the great variety and beautiful crystalline forms of the wide variety of zeolites present. Figure 12 *(opposite, bottom right)* shows one example. Zeolites are hydrated aluminosilicates that are produced by the alteration of feldspar. A large number of zeolite minerals occur naturally: the most common 25 are listed in Deer *et al.* (1985). The different zeolite minerals tend to occur in zones that reflect the

Figure 9 Infilled lava tube (height c. *1.5m) exposed on foreshore, Rituvik, Eysturoy, Faroe Islands (© Duncan Woodcock).*

Figure 10 Regular columnar jointing, Molin road cut, Suduroy, Faroe Islands. The columns are typically 1m wide and exhibit subhorizontal 'chisel marks' (© Duncan Woodcock).

temperature-time history of the cooling basaltic pile. Zoning of zeolites was first studied in eastern Iceland by Walker (1960); studies of zeolite zoning in the FIBG are in progress.

Conclusion

The recent study of the physical volcanology of the FIBG by Simon Passey represents an exciting new phase in the study of the geology of the Faroe Islands. The impetus for the work has been the ongoing search for oil in the Faroe-Shetland Basin and the need to understand the interbedded sequence of lava flows and volcaniclastic sediments that may host potential hydrocarbon reservoirs. In this area, oil geologists have suddenly become interested in volcanology!

References

Deer, W. A., Howie, R. A. and Zussmann, J. 1985 *An Introduction to the Rock-Forming Minerals*. Harlow: Longmans

Godinot, A. 1986 'Comments on "Pipe vesicles in Hawaiian basaltic lavas: their origin and potential as paleoslope indicators" '. *Geology* **16**, 90

Passey, S. R. and Bell, B. R. 2007 'Morphologies and emplacement mechanisms of the lava flows of the Faroe Islands Basalt Group, Faroe Islands, NE Atlantic Ocean'. *Bull Volcanology* **70**, 139–56

Passey, S. R. 2004 'The Volcanic and sedimentary evolution of the Faeroe Plateau Lava Group, Faeroe Islands and the Faeroe-Shetland Basin'. U Glasgow: unpubl PhD thesis

Philpotts, A. R. and Lewis, C. L. 1986 'Pipe vesicles — an alternate model for their origins'. *Geology* **15**, 971

Rasmussen, J. and Noe-Nygaard, A. 1970 *Geology of the Fearoe Islands (pre-Quaternary)*. Copenhagen: The Geological Survey of Denmark

Self, S., Keszthelyi, l. and Thordarson, Th. 1998 'The importance of pahoehoe'. *Ann Rev Earth and Planetary Sci* **26**, 81–110

Waagstein, R. 1988 'Structure, composition and age of the Faeroe basalt platform', in A. C. Morton and E. M. Parsons (eds) *Early Tertiary Volcanism and the Opening of the NE Atlantic*. London: Geol Soc Special Publ 39, 225–38

Walker, G. P. L. 1960 'Zeolite zone and dyke distribution in relation to the structure of the basalts of eastern Iceland'. *J Geol* **68**, 515–28

Walker, G. P. L. 1972 'Compound and simple lava flows and flood basalts'. *Bull Volcanology* **35**, 579–90

Walker, G. P. L. 1986 'Pipe vesicles in Hawaiian basaltic lavas: their origin and potential as paleoslope indicators'. *Geology* **15**, 84–7

Figure 11 Tree mould at the base of a lava flow, Sundshalsur, Streymoy, Faroe Islands (© Duncan Woodcock).

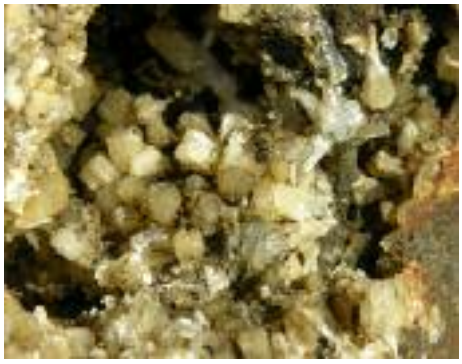


Figure 12 Zeolites partly infilling a large vesicle., Skardsgjogv, Suduroy, Faroe Islands (field of view 20mm × 30mm) (© Duncan Woodcock).

Book review

Parise, M. and Gunn, J. (eds) 2007 *Natural and Anthropogenic Hazards in Karst Areas: Recognition, Analysis and Mitigation*. London: Geological Society Special Publications 279 (ISBN 978-1-86239-224-3; hardback, 179pp; £70)

The Penguin Dictionary of Geology contains the entry: "Karst: Areas consist of terrain with distinctive landforms and drainage (often underground), mainly originating from solution erosion and commonly developed on carbonate rocks or evaporates."

This book is a collection of peer review papers presented at the Second General Assembly of the European Geosciences Union in Vienna, Austria, 24–9 April 2005, and other invited contributions. They highlight the hazards present in Karst areas, their recognition, analysis and mitigation, mostly through case studies from a variety of different karst areas around the world.

The editors M. Parise and J. Gunn briefly introduce the concept of karst areas as generally dominated by subterranean drainage, with a paucity of water flowing at the surface — a consequence of rapid water infiltration underground through discontinuities in the soluble rock mass. They conclude that the effects of this are two-fold: first, that 25% of the drinkable water in the world is thought to be contained within these resources; and second, that these regional groundwater bodies can easily be contaminated by human activities, which can introduce contaminants both from point sources and from dispersed infiltration. They briefly discuss how human activities can easily and severely impact karst areas, often irreparably, and conclude that the sustainable management of karst areas and there resources should be further studied to gain greater understanding of their character and for the benefit of all.

The papers are subdivided in to three key subject areas:

Collapse and subsidence hazards

This section comprises six papers that briefly discuss: (1) The identification of sinkholes in Florida by aerial photography. Comparing photographs from 1926, before urbanization, with post-urbanisation photographs from 1995 shows that 87% of the sinkholes found in 1926 can no longer be identified. (2) The dangers posed by additional anthropogenic loading over known or unknown caves and the safety considerations surrounding building in karst areas. (3) Sinkholes in Italy, their definition and the first results of their inventory and analysis. (4) The assessment of cover-collapse sinkholes in south-west Sardinia, complete with a preliminary hazard map. (5) Slope instability in southern Italy. And (6) the Magnetic detection of dolines in northern Spain.

Hydrological hazards

This section discusses several case studies: (1) The long-term effects of flooding coastal karst geomorphosites in central-eastern Sardinia in 2004. (2) An attempt to define protection zones around groundwater sources in carbonate aquifers. (3) A discussion on the speed of water flow through the Yorkshire chalk aquifer and the effect of water speed on the deposition of contaminants within the porous matrix of the chalk. (4) The use of stable isotope in sulphates as tracers of natural and contaminant sulphate sources in Sichuan, China. (5) A study on the vulnerability of the Alburni karst system in southern Italy. And (6) the impact of quarrying on karst aquifers in southern Italy.

Managing karst

This section has two papers. The first paper describes the natural and anthropogenic karst hazards present in Jamaica, of which about two-thirds of the landscape is thought to be karst. The second is an interesting paper examining the implications for the prehistoric cave paintings in the Grande Grotte Cave in Yonne, France of the growth of Biotic and abiotic calcite formations in the cave.

This publication is for specialists., but it presents well written and interesting papers that the enthusiast can follow. Some of the papers require commitment and studying in detail to get the best from them, but all of the papers can be appreciated at a more basic level as well.

— Mark Appleby, BSc Open

Book review

Welland, Michael 2009 *Sand: a Journey through Science and the Imagination*. Oxford: OUP (ISBN 978-0-19956-318-0; hardback, 331pp; £18.99)

As the title suggests, this is not a conventional earth sciences textbook, rather an account of a journey, or rather of two parallel journeys.

The first journey is upwards through a hierarchy of scales. The first chapter looks at individual sand grains: their mineralogies, morphologies and even their use in solving crimes. This is followed by a fascinating chapter entitled 'The strange world of granular materials', which discusses the often counterintuitive bulk behaviour of these materials, of which sand is a prime example.

Subsequent chapters look at larger scales, where the reader is introduced in a painless way to sand transport and deposition in fluvial, marine and desert environments, and then introduced to extraterrestrial sand. On the way we get to know some of the characters who carried out many of the classic studies on sand, such as Whitworth, Bagnold and Kuenen.

The second journey looks at the role that sand has had in developing our culture and society: the imagery of sand in mathematics, literature and language, and the use of sand as a medium for folk art both ancient and modern. Finally, it reviews the use of sand as a resource that underpins much of our modern technological society.

This is a superb book that has been very well produced and is a pleasure to read. You will learn (or be reminded of) much sedimentary geology as well as be entertained by a 'good read'.

— Duncan Woodcock, MA, BSc Open

An investigation into mud volcanoes and the relevance of methane hydrate to slope instability: a proposed research project

Kevin Brown

Introduction

This study aims to test the hypothesis that methane hydrate associated with mud volcanoes in the south-west Barents Sea can cause a tsunami that would be devastating to the west coast of Norway, to northern and eastern Scotland and to eastern England.

One of the largest known submarine slides is the Storegga slide, which occurred in the Barents Sea, and is dated at 8.2ka BP. It covers an area of 85–90,000km^2, has a volume of 3,300km^3 with an estimated area of slide scar of 30,000km^2 (Bunz *et al.* 2003). The evidence of the resulting tsunami can be found in the geological record as far south as the northern coast of France.

Today, these coastal areas are heavily populated and industrialised, and much of the coastline is vital to the economies of Norway and the UK. Any catastrophic slope failure, even on a small scale, could lead to a tsunami. If even a small tsunami of, say, 1–2m hit northern and eastern Scotland and eastern England at high tide it would invariably breach sea defences and cause tidal surges in river estuaries, with resultant flooding, loss of life and untold economic impact.

Location

The investigation would consider two locations: the first is the Hakon Mosby Mud Volcano (HMMV) located at 15º E, 72º N; the second is another mud volcano known as M2, located 60km to the south-east of HMMV (Fig. 1). Both HMMV and M2 were discovered accidentally by side-scan sonar and swath bathymetry cruises in 1989 and followed up in 1990 by Naval Research Laboratory Sea MARC II (Crane *et al.* 1995), a combined Russian, Norwegian and American expedition (Eldholm *et al.* 1999). HMMV and M2 lie at depths of *c*. 1,250m and *c*. 1,700m, respectively. Subsequent site investigations of HMMV using surface vessels and both manned and unmanned submersibles have revealed it to be a 'warm seep' with a high thermal gradient, seeping methane and oozing mud, with a unique ecosystem, as is often found at 'cold seeps' and hydrothermal vents (Vogt *et al*. 1997). M2 is probably a dormant mud volcano and possibly also a seep, although no evidence was found when it was discovered at the same time as HMMV. However, there have so far been no further investigations of M2 (Vogt *et al*. 1999) (Fig. 2).

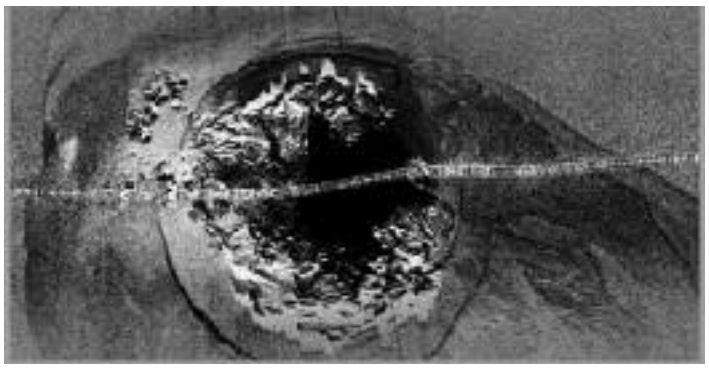


Figure 2 30kHz side-scan image of the Hakon Mosby Mud Volcano, 9 August 1996 (Vogt et al. *1999).*

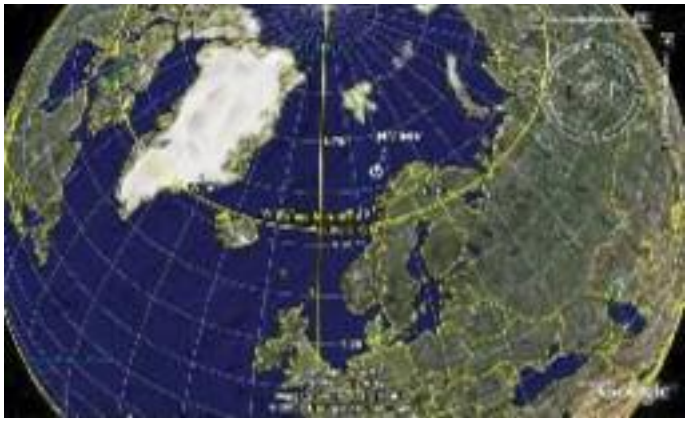


Figure 1 Map showing the location of the HMMV study area (small white circle, right of centre).

Methane hydrate

Methane hydrate in a marine environment forms either by thermogenic or by biogenic processes. The stability of methane hydrate on the sea floor is dependent on temperature, pore pressure, gas chemistry, pore water salinity and pore size distribution (Sultana *et al*. 2004). The combination of methane and water forming the hydrate produces an ice-like structure, which results in the cementation of sediments. However, any changes to the parameters that result in instability on the sea floor can lead to dissociation and melting, resulting in weakening and under-consolidated sediments (Sultana *et al*. 2004). Changes to temperature and pore fluid pressure are likely to occur in gas hydrate fields in the future owing to climate change; and as sea-level temperatures increase, dissociation will take place and increasing sea levels will result in higher pore fluid pressure and therefore lead to weakening and/or blowouts.

Heat flow anomaly

The cause of the high heat flow anomalies at HMMV and M2 are currently undetermined. Heat flow measurements west of the Senja Fracture Zone (SFZ) are relatively constant, averaging 63.5 ± 5.3 mWm^{-2}. Heat flow measured at HMMV was 298 and 377 mWm-2 and the measurement at M2 was 108 mWm^{-2}. Seismic investigations at HMMV were unable to penetrate the mud because of the noise caused by gas hydrate bubbles.

Three hypothesis have been put forward for the source of the heat flow anomaly. Crane (see Vogt *et al*. 1999) suggests that most of the helium from the HMMV source "is of a non-atmospheric crustal origin" and is indicative of a dyke intrusion caused by reactivation of the SFZ or igneous activity in the Vestbakken volcanic province. A 1–2km vertical structure is seen on seismic section at a depth of 3–6km, but the resolution is not good enough to make an interpretation. Hjelstuen *et al.* (1999) suggest a mixed biogenic-thermogenic origin based on isotopic and chemical analysis of pore waters. They suggest an origin near the base of the 3.1km sediments, which have been dated at 2.3Ma (Vogt *et al*. 1999). Eldholm *et al*. (1999)

OUGS Journal 31 (1–2) 2010, 17–20
© OUGS ISSN 0143-9472

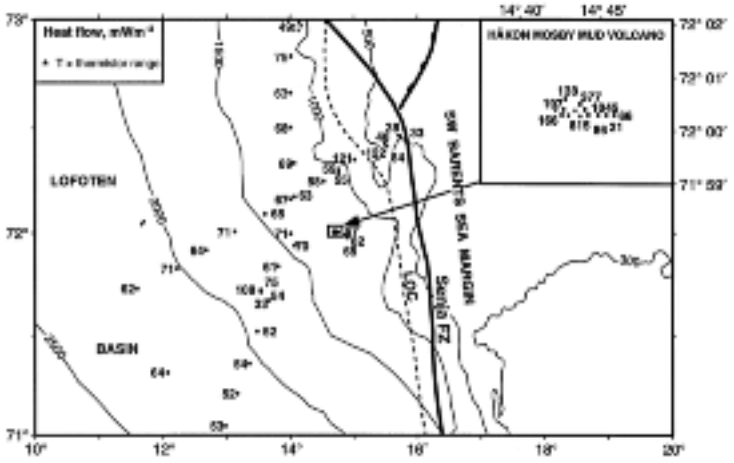


Figure 3 HMMV (inset) shows a high level of heat flow compared to the surrounding area. LOC is the limit of well defined oceanic crust in seismic profiles (Faleide et al. *1993).*

suggest that a sub-bottom thermal gradient of 5–10 C° m^{-1} is comparable to that at depths of 2–3km, and so suggest that heat is transferred to the sea floor by mud and/or by pore fluids rising too fast for thermal equilibrium to occur (Fig. 3).

Objectives

The objective is to test the hypothesis that dissociation of methane hydrate combined with a mud volcano could trigger a catastrophic slope failure resulting in a tsunami hitting western Norway and the north-eastern UK. HMMV is a an active mud volcano and warm seep, and evidence for three separate mud flows was found during the first expedition in 1989 (Crane *et al*. 1995). M2 is believed to be inactive but, as noted above, no study has taken place since its discovery in 1989.

Three primary objectives have been identified:

1. to discover how and why mud volcanoes switch on and off (as observed by the separate mud flows at HMMV); and to surmise, if M2 is inactive, will it reactivate and what will be the trigger;
2. to investigate the source of the high heat flow at HMMV and to take detailed measurements at M2 to ascertain if it is completely dormant;
3. to compare the history of HMMV and M2 and to ascertain whether the combination of methane hydrates and a mud volcano is likely to lead to a slope failure triggering mass failure and resulting in a tsunami.

Methodology

The manned research submersible ALVIN would be used to make five dives: two dives at the site of HMMV and three dives at the site of M2. There are considerable data in the literature on HMMV, so research here would be confined to a magnetic survey, coring of upper sediments, temperature measurements and water chemistry analysis.

The magnetic survey would use a three-axis fluxgate vector magnetometer with data logging integrated into Alvin's data system. This system was designed for ALVIN and is known to work well. The magnetic survey would look beneath the sediments and confirm whether or not the 1–2km vertical structure is a dyke and whether it is the source of the high temperature gradient.

Coring would be done using a hydrate drill designed by The National Energy Laboratory in the U.S.A. The drill system can take six samples to a depth of 300mm and return the hydrate to the surface intact due to pressure maintenance. Past missions have seen the hydrate dissociate during the return to the surface. Data obtained from the cores would be compared to past data to ascertain if there has been an increase or decrease in the chemical properties of the hydrate, thus indicating more or less activity since earlier measurements were taken (Fig. 4).

Video recording would be continuous to give a detailed visual record of the surface; digital photography would also be used, as required.

Temperature data and water samples would be collected during the decent and ascent phases, and also while on the bottom. This data would be collected at the same locations as previous studies so that the data sets can be compared.

Investigation of M2 would follow the same pattern of that at HMMV, but in more detail. No seismic profile is available, so a more detailed magnetic study would also be undertaken. Temperature data would be collected at more regular intervals, as would water samples. Twelve core samples would be collected, enabling the analysis of the sediments across the volcano and confirm, or not, the presence of methane hydrate (*see* Figs 5–7, *opposite*).

Figure 4 Hydrate drill with six detachable coring bits in lab (The National Energy Technology Laboratory. The National Methane Hydrates R&D Program DOE/NETL Methane Hydrate Projects).

Research plan

The project would begin with the research team flying to Norway to join the research vessel *Atlantis* before sailing to the research area. On-site research would be conducted as described above in 'Methodology'. The research would be split into two phases and five dives. Phase one would consist of three dives at the M2 site. The primary task on dive one would be to carry out a magnetic survey, continuous temperature data collection and taking water samples at regular intervals, providing this does not detract from the magnetic survey. Dives two and three would concentrate on coring surface sediments, as the equipment limits this to six cores per day. ALVIN's video and digital cameras would be used as required to produce a visual map in order to examine lateral changes of M2.

Phase two would take place at HMMV. As before, the primary task on dive four would be to complete a magnetic survey in order to get resolution beneath the methane, which seismic data cannot penetrate. Temperature measurements would be recorded continuously and water samples taken if it does not detract from the seismic survey. The primary objective on dive five would be to collect, for comparison, six core samples from close to where

Figure 5 View of central dome of HMMV (Jørgensen and Boetius 2007).

previous studies have sampled. Temperature would be measured continuously and water samples taken. Video recording on both days would provide evidence of any new mud flows and hydrate renewal and provide for remapping of the surface.

Analysis

Magnetic survey data would be combined with seismic data obtained in previous studies from the HMMV site in order to understand the sub-sediment geology and to interpret the source of the heat anomaly. The methane hydrate cores to be returned intact, without dissociation taking place, would be chemically analysed. Biogenic methane is depleted in ^{13}C and thermogenic methane contains more ethane and propane, so a ratio of biogenic to thermogenic methane would be determined, giving an indication of the source. At the HMMV site sediment cores, temperature and water chemistry data would be mapped to provide a comparison to previous data. Mud flows would be mapped using data collected on site and from the video recordings. Any changes in the data between this study and the previous studies would indicate if HMMV has reduced or increased its activity.

Data analysis of M2 would reveal if there has been any recent activity and the extent of past mud flows would indicate the extent of past activity. If methane hydrates are found or methane is detected in the surrounding water this would indicate a seep. The data from both sites would be compared for similarities, and compared to the literature.

Figure 6 Methane bubbles out (Jørgensen and Boetius 2007).

Justification and benefits

The recent discovery of a mud volcano combined with a warm methane hydrate seep situated in a slide scar on the continental slope in the south-west Barents Sea has raised the question of whether the mud volcano/seep preceded slope failure or resulted from it. This proposed study would enable a more in-depth understanding of the processes of hydrate formation in the arctic environment, which would have relevance beyond the study because any future manned mission to Mars would need to extract the methane hydrate known to exist under the cold polar regions for fuel and water (Pellenbarg 2001).

Dissociation of methane hydrate leads to methane gas entering the atmosphere, with consequences for global warming, which in turn warms the ocean and results in more dissociation. It is the dissociation that can potentially lead to under-consolidated sediments and slope failure when combined with mud flow. Once a mass wasting process begins it can pick up momentum, causing failure along a greater area, and could result in catastrophic slope failure if the slope is big enough and if enough unconsolidated sediments are present.

Figure 7 Algal mats (dark areas) thrive on the methane hydrate (white) (Jørgensen and Boetius 2007).

Understanding the mechanism that switches mud flows on and off is important to future geohazard assessment. Pore fluid pressure is an important factor and understanding of the source of fluids would lead to an understanding not just of HMMV and M2, but also of similar systems elsewhere in the world.

Temperature and chemical analysis from the study areas would add to data already collected and would be relevant to regional studies of Arctic sea water chemistry and of climate change more generally.

The results of this study, combined with data from previous studies, would result in an understanding of the relationship between methane hydrate, mud volcanoes and catastrophic slope failure. If a connection is proved, then future studies could be undertaken to determine the abundance of these systems in the region and to assess the risk posed to Norway and the UK from tsunamis.

References

Bunz, Stefan, Mienert, Jurgen and Berndt, Christian 2003 'Geological controls on the Storegga gas-hydrate system of the mid-Norwegian continental margin'. Dept. Geol., U. Troms, Dramsveien 201, 9037, Troms, Norway. *Earth and Planetary Science Letters* **209**, 291–307.

Crane, K., Vogt, P. R., Sundvor, E., Shor, A. and Reed IV, T. 1995 'Sea MARC II investigations in the northern Norwegian-Greenland Sea'. *Meddelelser Norsk Polarinstitut* **137**, 32–140

Eldholm, O., Sundvor, E., Vogt, P. R. B., Hjelstuen, O., Crane, K., Nilsen, A. K. and Gladczenko, T. P. 1999 'SW Barents Sea

continental margin heat flow and Haskon Mosby Mud Volcano'. *Geo-Marine Letters* **19**, 29–37

Faleide, J. I., Vasgnes, E. and Gudlaugsson, S. T. 1993 'Late Mesozoic–Cenozoic evolution of the south-western Barents Sea in a regional rift-shear tectonic setting'. *Marine and Petroleum Geol* **10**, 186–214

Hjelstuen, B. O., Eldholm, O., Faleide, J. I. and Vogt, P. R. 1999 'Regional setting of Haskon Mosby mud volcano, SW Barents Sea margin'. *Geo-Marine Letters* **19**, 22–8

Jørgensen, Bo Barker and Boetius, Antje 2007 'Feast and famine — microbial life in the deep-sea bed'. *Nature Reviews: Microbiol* **5**, 770–81 (October); www.nature.com/nrmicro/journal/v5/n10/full/nrmicro1745.html

Pellenbarg, Robert E. 2001 'Methane and carbon dioxide hydrates on Mars: are there sufficient natural resources on Mars to sustain human habitation?'. Conference on the Geophysical Detection of Subsurface Water on Mars (2001)

Sultana, N., Cochonata, P., Fouchera, J.-P. and Mienert, J. 2004 'Effect of gas hydrates melting on seafloor slope instability'. *Marine Geol* **213**, 379– 401

Vogt, P. R., Cherrkashev, G., Ginsburg, G., Ivanov, G., Milkov, A., Crane, K., Lein, A., Sundvor, E., Pimenov, N. and Egorov, A. 1997 'Mosby mud volcano provides unusual example of venting'. *Haakon.Eos* **78**, 549–57

Vogt, P. R., Gardner, J. and Crane, K. 1999 'The Norwegian–Barents–Svalbard (NBS) continental margin: introducing a natural laboratory of mass wasting, hydrates and ascent of sediment, pore water, and methane'. *Geo-Marine Letters* **19**, 2–21. Springer-Verlag

---

Book review

Bennett, Matthew R. and Glasser, Neil F. 2009 *Glacial Geology: Ice Sheets and Landforms* (2 edn). Oxford: Wiley-Blackwell (ISBN 978-0-47051-690-4; hardback, xiv + 386 pages; £85. Also available in paperback, ISBN 978-0-47051-691-1; price unknown)

This is an expensive (in hardback) and technical monograph and student text. I was unable to find the paperback listed on Amazon, so cannot state the price of the cheaper-bound edition.

It comprises 12 chapters. The first, the Introduction, defines 'Glacial Geology', explains why it is important and declares the aims of the book. It is the study of sediments and landforms made by glaciers and ice sheets, both past and existing. The aims are to assess past and present glaciers and landforms, give their history and impact on the face of the earth, examine how they form and operate, describe what forms they leave behind as geological evidence and to describe their present conditions and relevance to current climate studies.

Chapter 2 describes glacial landscapes around the world.
Chapter 3 examines ice formation and flow; patterns and rates; and glacier response to climate change.
Chapter 4 examines water in glaciers: sources of, storage, hydrological systems, subglacial pressure, discharge and erosion, and methods of studying glacial hydrology,
Chapter 5 focuses in detail on glacial erosion: abrasion and 'quarrying', patterns and rates of erosion.
Chapter 6 describes glacial landforms that result from erosion: covering micro- to macro-scale features, how to recognise and study them, and large-scale landscapes that result from glacial erosion.
Chapter 7 examines in more detail types and rates of glacial erosion debris, and its entrainment, transport and transfer.
Chapter 8 focuses on direct glacial sedimentation and on fluvial sedimentation, comparing and contrasting them.
Chapter 9 examines in detail glacial deposition left on the land: moraines, subglacial forms, and glaciofluvial ice-margins and subglacial forms.
Chapter 10 describes in detail lacustrine and marine sedimentations and environments; and distinctions between glaciofluvial on the one hand and glaciomarine diamicts and glacial tills on the other.
Chapter 11 describes the mechanics and evidence of glaciolacustrine and glaciomarine deposition ands the landforms they create.
Chapter 12 focuses on palaeoglaciology: methods of examination and study; the 'Key Landforms' used in this study; subglacial 'thermal regimes'; and reconstructions of palaeoglacial landforms.

Each chapter finishes with a summary of the detailed discussion within the chapter and ends with a suggested reading list. These reading lists are extensive, in most cases several pages long.

Key terms are printed in *italic* at first mention, and also when they are particularly pertinent to the subject being discussed. Throughout the book, key topics are highlighted in blue boxes, describing types, processes, methodologies and case studies.

The book is profusely illustrated throughout. There are aerial, satellite and land-based photographs of glaciers and glacial forms and landscapes, both in black and white and in colour. Figures — line, schematic, reconstructional, cartoon and colour-inhanced or highlighted — help to demonstrate the topics. They show real examples as well as schematic and diagrammatic explanations of the textual matter.

There is no bibliography, as such, for the 11 reading lists (from chapter 2 to chapter 12) fulfil that purpose. There is an adequate index of nine pages, in which the major topical terms are amplified by secondary-level entries.

The text is technical but not difficult to read; it is mostly devoid of over-long sentences and proceeds in logical stages through the subject matter, building on one chapter's topics in successive chapters. When you have finished the book you will certainly understand a lot more about glaciers, their workings, environments and recognition of their effects on landscapes and the landforms they create than you started with. Despite being a technical monograph, any professional or student geologist well into his or her second or third year would gain much from this thorough treatment of glacial geology past and present.

— David M. Jones, BA UC Berkeley, MA, PhD UC London, BSc Open

A predecessor of Darwin? The surgeon William Lawrence

Philip Clark

At the Darwin centenaries in 1909 and 1959 one name mentioned as a significant predecessor of Darwin was William Lawrence, FRS. C. D. Darlington, Professor of Botany at Oxford, published a small book in 1959 commemorating *Darwin's Place in History*. In it he included a short chapter on "The suppression of Lawrence", and wrote of Darwin and Huxley: "Neither of them supports or contradicts Lawrence on the theoretical issues he examines. If either of them had done so he would have been able to write a better book" (Darlington 1959, 22). In fact, this was rather exaggerated: Lawrence was no evolutionist and believed in the immutability of species, although he noted the rise of *varieties* both in nature through geographical separation and in domesticated animals through breeding — two of Darwin's starting points. Lawrence explicitly derided the idea that men and monkeys might be related. "The peculiar characteristics of man appear to me so very strong, that I not only deem him a distinct species, but also put him in a separate order by himself. His physical and moral attributes place him at a much greater distance from all the other orders of mammalia than those are from each other" (Lawrence 1819, 132). Two articles, one by Peter Mudford in the *Journal of the History of Ideas* in 1968, and a longer one by Kentwood Wells in the *Journal of the History of Biology* in 1971, showed conclusively how thin were the claims for Lawrence as a significant predecessor of Darwin.

But Lawrence is important and interesting — and not just because he introduced into the English language (from the German of Gottfried Reinhold Treviranus) the word 'biology' for the science of life. Apart from the intrinsic interest of the story of "one of the ablest men whom I have known" having been "well-nigh ostracised for his book *On Man*", as T. H. Huxley put it (Huxley 1903, 283; quoted in Darlington 1959, 22), Lawrence's lectures at the Royal College of Surgeons, still highly readable, have an important place in the question of where life comes from and in the endeavour to see clearly man's place in nature. They have indeed been described as "the beginning of modern anthropology in this country" (Plarr 1930). Lawrence is one of the scientists whose work had repercussions on society discussed recently by Richard Holmes in *The Age of Wonder* (1908).

The influence on Darwin was actually negative: how not to present speculations, upsetting everyone. Probably the knowledge of what had happened to Lawrence was one of the reasons why Darwin sat on his ideas for so long. The only idea of actual interest Darwin found in Lawrence's book was that of sexual selection in man (Wells 1971, 337–8). But the influence on his fellow discoverer of the theory of natural selection, Alfred Wallace, was more positive. Kentwood Wells wrote: "It appears that at the very beginning of his speculations on evolution, Wallace had found in Lawrence a possible mechanism of organic change, that of spontaneous variations leading to the formation of new species" (Wells 1971, 342).

A promising young surgeon

Lawrence was the elder son of a Cirencester doctor, born there in July 1783. His father determined that his boy should succeed in medicine, but as a surgeon, not as a country physician. There was to be no local apprenticeship for him — not even in the nearest

William Lawrence, surgeon.

big city, Bristol. There was only one place — London. The younger Lawrence did not go to London, as he might today, at 19 or 20, but at 15, for it was only February 1799 when his father sent him to St Bartholomew's Hospital to be apprenticed to the renowned surgeon Abernethy for seven years at a premium of 400 guineas. It is amazing how young medical education began in those days; 26 years later, Charles Darwin was not yet 17 when he went to study medicine in Edinburgh. Lawrence lodged with Abernethy for his first years in London and was his favourite pupil; and did so well that Abernethy appointed him his demonstrator of anatomy in 1801. That year he first showed interest in anthropology, reading a paper 'On the varieties of human species' to the hospital's Medical and Philosophical Society.

Lawrence received the diploma of the newly reconstituted Royal College of Surgeons in 1805 when he was just 22. The incomplete transformation of the Surgeons' Company into a truly representative college representing equally all surgeons in England is the background to Lawrence's stormy medical career. He was elected to one of the coveted positions of Assistant Surgeon at St Bartholomew's in 1813. He soon added other appointments: Surgeon to the London Infirmary for Diseases of the Eye in 1814, Surgeon to the Royal Hospitals of Bridewell and Bethlem in 1815 and Professor of Anatomy and Surgery at the Royal College of Surgeons in the same year. But 'Barts' was always the hospital with which he was most closely connected, despite his gradual estrangement from Abernethy.

OUGS Journal 31 (1–2) 2010, 21–7
© OUGS ISSN 0143-9472

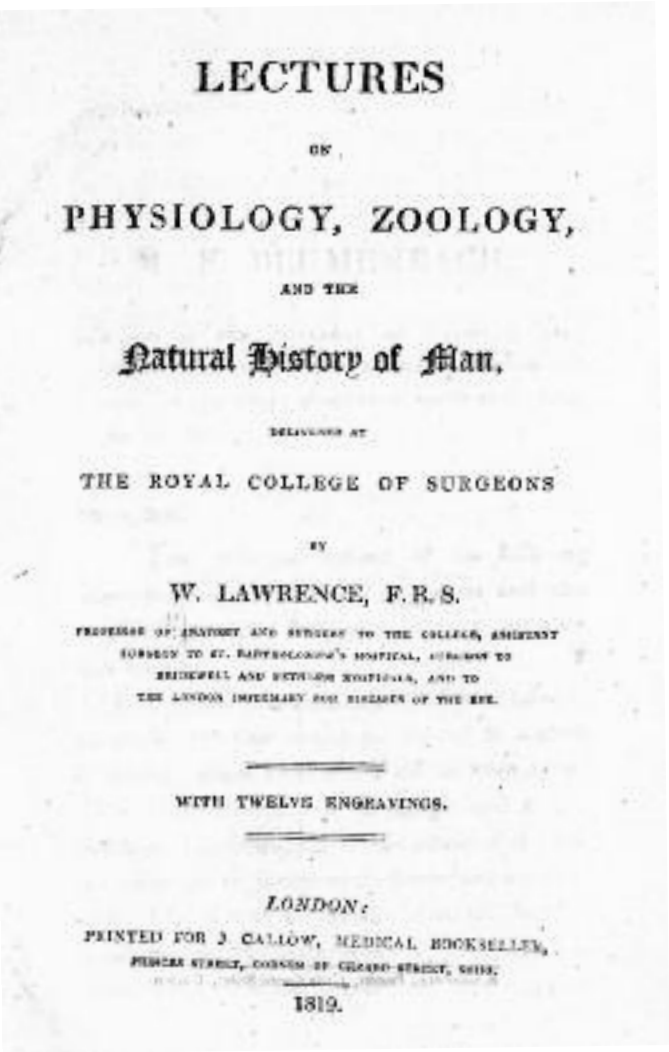
This estrangement was partly because of the 'materialism' he advocated as against Abernethy's 'vitalism'. It may also have been because Abernethy became jealous of his protégé. Lawrence, however, became surgeon to St Bartholomew's in 1824, and eventually succeeded Abernethy as lecturer on surgery. By then Abernethy had been the chief mover in the founding of St Bartholomew's medical school, thus removing the need for apprenticeships. Lawrence, who had lectured for a time in surgery at a rival medical school in Aldersgate Street, paid warm compliments to Abernethy for this when chairing the 'dinner for gentlemen educated at St. Bartholomew's Hospital' in 1824. When Lawrence finally retired from St Bartholomew's in 1865 he was given the complimentary title of 'Consulting Surgeon', so it could be said when he died in 1867 that he had been connected with the hospital for 68 years!

His career as a surgeon need not concern us, but in view of his celebrated lectures it is relevant that he was an impressive lecturer to trainee surgeons, as we learn from a description by another famous surgeon, Sir James Paget, looking back in old age to the lectures from Lawrence he attended in the 1830s. "He came in quietly, and after sitting for about half a minute, as if gathering his thoughts, began, in a clear, rather high note, speaking quite deliberately in faultless words as if telling judiciously that which he was just now thinking. There was no hurry, no delay, no repetition, no revision: every word had been learned by heart, and yet there was not the least sign that one word was being remembered. It was the best method of scientific speaking that I have ever heard" (Paget 1901, 45; quoted in Wells 1971, 321–2). There seems also to have been something theatrical about his delivery, though, for the obituaries in both *The Times* and in the *Gentlemen's Magazine* compared Lawrence to the celebrated actor Charles Kemble.

Despite being himself a brilliant surgical lecturer, in his radical days Lawrence pushed for better practical training for surgeons as well. In speeches made in 1826 at two meetings of members of the Royal College of Surgeons, he emphasised the practical nature of surgery and the consequences of this for medical training. Anatomy could not just be taught by lectures; and physiology, pathology, pharmacy, midwifery and diseases of the eye, were all missing from a surgeon's training at that time (Desmond 1989). Lawrence practised and wrote about many branches of medicine, but his chief speciality was as an eye surgeon. He worked at one of the first hospitals specialising in the diseases of a single organ, the London Infirmary for Diseases of the Eye, and his treatise *On the Diseases of the Eye* was a pioneer work (for Lawrence's contributions to ophthalmology, see Chance 1926).

Controversial lectures

But Lawrence is not chiefly remembered now for his achievements as a mature and leading surgeon. It is his earlier years — up to the age of 40 — that are of interest to us in the context of Darwin. At 18 he published a translation of a Latin work on the human arteries by an Uppsala professor; at 26 he was an internationally recognised authority on hernias. At 30 he was a Fellow of the Royal Society. This was even then remarkably early, but the great President of the Society, Sir Joseph Banks, kept a watchful eye on rising young scientists, and supported his election. Banks had noticed Lawrence when he was still a medical student, recommending him to the conservator of the Hunterian Collection of comparative anatomy specimens. Lawrence later


LECTURES

ON

PHYSIOLOGY, ZOOLOGY,

AND THE

Natural History of Man,

DELIVERED AT

THE ROYAL COLLEGE OF SURGEONS

BY

W. LAWRENCE, F.R.S.

PROFESSOR OF ANATOMY AND SURGERY TO THE COLLEGE, ASSISTANT SURGEON TO ST. BARTHOLOMEW'S HOSPITAL, SURGEON TO BRIDEWELL AND BETHLEM HOSPITALS, AND TO THE LONDON INFIRMARY FOR DISEASES OF THE EYE.

WITH TWELVE ENGRAVINGS.

LONDON:

PRINTED FOR J. CALLOW, MEDICAL BOOKSELLER, PRINCES STREET, CORNER OF CHANDOS STREET, COVENT GARDEN.

1819.

Title page of the Lectures on Physiology, Zoology, and the Natural History of Man.

paid a warm tribute to Banks in his lectures, saying "In the unrivalled library of Sir Joseph Banks, and in the more uncommon liberality with which it is opened to all who are engaged in scientific pursuits, the naturalists of this country enjoy an eminent advantage. The powerful and munificent patronage of this public-spirited individual is freely bestowed on all branches of science: it … takes the form of active and warm assistance in all scientific undertakings that promise to promote public utility …" (Lawrence 1819, 30).

Lawrence as a medical student studied anthropology under Banks' old friend Blumenbach, and is said to have been "noted for his brilliance and intellectual daring" (Holmes 2008, 310). Blumenbach was professor of medicine at Göttingen, which was in the Electorate of Hanover, ruled by Banks's powerful ally, King George III. This facilitated cooperation between the president of the Royal Society and the German pioneer anthropologist, and Banks arranged to have many human skulls from around the world sent to Blumenbach. It was to Blumenbach that Lawrence dedicated his collected lectures, writing that he was "recommending to imitation the example you have set of combining together anatomical, physiological, and zoological pursuits, and advancing them by reciprocal illustration" (Lawrence 1819, iv). Not only did Lawrence draw more examples from Blumenbach than from any other source, but also the introduction to the

lectures of 1818 shows a programme inspired by the Göttingen professor: *The Cultivation of Zoology and comparative Anatomy recommended as Branches of general Knowledge, and as an interesting Department of Philosophy* [it would be half a generation before the word 'science' and the newly minted designation 'scientist' fully displaced the older term 'natural philosophy']: *their Relation to various Questions in general Philosophy exemplified in the Gradations of Organisation, and the Doctrine of final Causes. Examples of the Aid they are capable of affording to Geology and the physical History of the Globe. Their importance to Physiology, and consequently to the scientific Study of Medicine. Objects of Inquiry in the Animal Kingdom, and mode of Investigation: Anatomy, Physiology, Pathology* (Lawrence, 1819, 38).

It was then, as Professor of Anatomy and Surgery to the College of Surgeons from 1815, that Lawrence "delivered those famous lectures on Comparative Anatomy, Physiology, Zoology and the Natural History of Man, which astonished so many, and aroused such animosity, that had their author been a man of less capability, he would, beyond doubt, have been ruined for life" (Savory 1868, 3). Both the lectures of 1816 and the more famous lectures given in 1817 and 1818 — printed in 1819 — often known as 'On Man or The Physiology of Man', are indeed powerful pieces of writing. They caused a tremendous storm at the time, and are worth reading today for the enjoyment of the style and argument.

The lectures consist first of the preface to the 1817 lectures, an expansion of the subject of his inaugural lectures of the previous year, on the history of comparative anatomy. His aim is to show that national prejudices should be disregarded in science: "Our insular situation, by restricting intercourse, has contributed to generate a contempt of foreigners, and an unreasonable notion of our own importance, which is often ludicrous; always to be regretted" (Lawrence 1819, 17). Lawrence first talks of the great French 18th-century tradition of Buffon and Daubenton, then of the Germans Camper, Pallas and Haller, before moving to more recent anatomists, culminating in the German Blumenbach and the French Cuvier; he also speaks of Hunter, the totemic figure who died when Lawrence was still a boy, and whose collection of specimens, as we have seen, Lawrence had begun to study at an early age. Hunter's memory was especially revered by Abernethy. Lawrence makes the point that Hunter "became acquainted with the labours and discoveries of all other countries" (Lawrence 1819, 26). This gives him the opportunity to make digs at Abernethy, whose lectures of the previous year had spoken as if Hunter owed nothing to any foreign scientist, was clearly superior to Cuvier and had in fact been the inspiration of the more recent foreign anatomists. This strictly professional quarrel about anatomy, which, quite apart from the subject of 'vitalism', divided the two surgeons, would of itself have led many in the medical profession to believe that Lawrence had behaved badly in attacking his former master.

However, this would not have excited a wide general public without the reason for this preface: a *Reply to the Charges of Mr. Abernethy*. These 'charges' had come in Abernethy's lectures, and were attacks on points in Lawrence's lectures of 1816, *An Introduction to Comparative Anatomy and Physiology*. Lawrence says that in his lectures he had made a "few remarks on life", which Abernethy had blown up into "the charge of having perverted the honourable office [of professor at the College of Surgeons] … to the very unworthy design of propagating opinions detrimental to society, and of endeavouring to enforce them for the purpose of loosening those restraints, on which the welfare of mankind depends" (Lawrence 1819, 3). Lawrence had proclaimed in direct opposition to Abernethy that the power that animates animals "from an oyster to a man" resists abstraction from matter: "The motion proper to all living bodies, or in one word, life, has its origins in that of their parents." There was no 'vital principle', which he scathingly said had been "compared to magnetism, to electricity, and to galvanism; or it is roundly stated to be oxygen. 'Tis like a camel, or like a whale, or like what you please …" (Lawrence 1816, quoted in Butler 1994, xvii–xxi; and in Holmes 2008, 312). Abernethy, thus compared to foolish Polonius, in return attacked Lawrence in terms that Lawrence said "alleged that there is a party of modern sceptics, co-operating in the diffusion of these noxious opinions with a no less terrible band of French physiologists, for the purpose of demoralising mankind!" (Lawrence 1819, 4).

So in his 1817 lectures Lawrence vigorously defended himself, and reasserted his opposition to 'vitalism', to Abernethy's traditional belief that life was something added from outside to inanimate matter, and pushed what became the general view and still is today, that life arose from the organisation of matter. "That life then … is immediately dependent on organisation, appears to me, physiologically speaking, as clear as that the presence of the sun above the horizon causes the light of day … I say, physiologically speaking … because the theological doctrine of the soul, and its separate existence, has nothing to do with this physiological question, but rests on a species of proof altogether different. These sublime dogmas could never have been brought to light by the labours of the anatomist and physiologist. An immaterial and spiritual being could not have been discovered among the blood and filth of the dissecting-room …" (Lawrence 1819, 7–8).

The 1818 lectures form far the largest part of the 1819 published book. An introductory lecture gives the broadest justification for the study of zoology and comparative anatomy, including the value of fossils, "almost the only accurate data for any reasonable conclusions respecting the number, nature, and progressive series of the changes which have affected the earth's surface; of the preadamitic revolutions of the globe …" (Lawrence 1819, 55). The next two chapters on the study of physiology and the nature of life restate the objections to a 'vital principle', and contend for thought as "an act of the brain", not of "an immaterial substance, residing in or connected with it" (Lawrence 1819, 105). The remainder of the book, more than three quarters of the whole, is *On the Natural History of Man*.

A furious response

The scandal the lectures caused when they were published was partly due to the great strength of conservatism in the years after the battle of Waterloo. Most leaders of the establishment thought that the really important issue of the day was not to provoke a French-style revolution in Britain. Even "geology, according to conservative commentators throughout the early nineteenth century, was a symptom of 'the *malaria* of French philosophy' " (Lewis and Knell 2009, 331). Lawrence quoted French savants whose views had radical implications, like Cuvier and Bichat; he had suspect friends in England, such as the radical publishers Richard Carlile and William Hone, two of the greatest heroes of the story of how a free press came to exist in Britain.

So when these striking lectures were published with a firm defence of observation rather than tradition, and suggestions that the Bible was not the last word on the nature of man, there was trouble. Lawrence was attacked not just by his own profession, but also from pulpits and in newspapers. It was "the first great scientific issue that widely seized the public imagination in Britain, a premonition of the debate over Darwin's theory of evolution by natural selection, exactly forty years later" (Holmes 2008, 313). The very influential *Quarterly Review* in a long article in July 1819 commented on "the evil consequences arising to society from the unguarded adoption [of Lawrence's views]" (*Quarterly Review* 1820). The article, although primarily attacking Lawrence, was a review of all the debate about the principle of life over the past few years, and was part of a campaign against cultural subversion, which the *Quarterly Review* kept up for several years. Religious speculation, it was thought, led to political radicalism and should be suppressed (Butler 1994, 235ff). Remarks by Lawrence about the United States, a nation "sacred to civil liberty where man may walk erect in the conscious dignity of independence … and enjoy full freedom of word and action; without the permission of those combinations or conspiracies of the mighty, which threaten to convert Europe into one great state prison" (Lawrence 1819, 37), and about the harmful effects of inbreeding in the royal houses of Europe (*ibid*. 460) proved to his critics how dangerous his observations were!

Many other publications followed the *Quarterly Review*'s lead. A pamphlet by 'Oxonian', for example, was called *The Radical Triumvirate; or, Infidel Paine, Lord Byron, and Surgeon Lawrence, colleaguing with the Patriotic Radicals to emancipate mankind from all laws, human and divine* (Anon. 1820). Lawrence had suddenly become a household name. Felicia Dorothea Hemans published a poem, *The Sceptic*, which probably had Lawrence in mind as well as Byron. In fact, it was Shelley rather than Byron who actually knew Lawrence and was influenced by him. Lawrence had certainly invited the opposition of conservative Christians, pointing out that, "the entire, or even partial inspiration of the various writings comprehended in the Old Testament has been, and is doubted by various persons … The account of the creation and subsequent events, has the allegorical figurative character common to eastern compositions …" (Lawrence 1819, 248).

There were of course supporters too, and eventually books written in support of Lawrence. "*The Monthly Magazine* for June 11, 1819 compared Lawrence to Galileo …" (Wells 1971, 336). Carlile's *Address to the Men of Science* (1821) urged Lawrence and others to retain their intellectual independence. In 1823 Thomas Forster published *Body, Life, and Mind* (as he subsequently called it; see Philostratus, pseud. 1823), in which he strongly attacked Abernethy's treatment of Lawrence, to the point of breaking off a long-standing friendship with the former.

The lectures withdrawn

Lawrence counted the cost, and found it too great. He withdrew his published lectures, mainly because he was threatened with the loss of his position as Surgeon to the Royal Hospitals of Bridewell and Bethlem; but they started to come out in pirate editions (Carlile's, possibly with Lawrence's connivance). In 1822 Lawrence sued a bookseller for breach of copyright and obtained an injunction enjoining him to stop publishing on the grounds of 'piracy'. However, the Lord Chancellor then dissolved the injunction after it had been argued in court that the lectures were so blasphemous that Lawrence could not have copyright in them. These arguments seem to us extraordinary. "The object of the publication", said learned counsel, "was to send out to the world the doctrine, that when man dies, his soul dies with him; denying the immortality of the soul. He [the lawyer] would admit that the lectures were most ably and eloquently written, which only tended to give the poison they contained greater influence over weak minds" (*The Times* 1822, 25 March, 3). Lawrence's lawyers did not do him much service, as they spent most of their time on hair-splitting theological points, trying to show that the lectures fitted in with what orthodox Christian writers had said. It was thought by many that they should have concentrated on showing how necessary it was to uphold an author's right in his works, whatever these contained.

Some of the pirate editions were published in the U.S.A., where at the time no copyright law existed, which was a situation that annoyed British writers throughout the 19th century from Dickens through Trollope to Kipling. After Lawrence's death, *The Times* repeated the calumny that he had sold the *Lectures* to "a publisher of seditious and blasphemous works, by whom the books were sent to America" (*The Times* 1867, 10).

Today, although the question of where life arises from is still not completely understood, it is the part dealing with the natural history of man that is the most interesting, as Lawrence poses the question: "Are all Mankind of one Species? Or do they belong to more than one?" (Lawrence 1819, xiii). It is a question, he says, not to be "determined by a priori arguments", nor by the account of creation in *Genesis*, nor by history. Only an exhaustive anatomical and physiological examination of the different races will do. This he then proceeds to do, in several chapters, and concludes that from this data it seems clear "That the human species, therefore, like that of the cow, sheep, horse, and pig, and others, is single; and that all the differences, which it exhibits, are to be regarded merely as varieties" (Lawrence 1819, 548).

How the varieties arose, though, is a more difficult question to answer, although Lawrence is most diligent in considering various possibilities. It is pleasant to discover that he was not inclined to regard other races as different species (though in old age he was more so inclined); but taking from Blumenbach 'the five varieties' of humanity, he unfortunately placed greater emphasis than his master on the gulfs between these varieties, and held the belief that what Blumenbach had called the 'Caucasian' race, that is of course 'white' people, was physically, mentally and morally superior to the others ('Mongolian', 'Ethiopian', 'American' and 'Malay') (Lawrence 1819, 551ff; see also Blumenbach 1807). Lawrence duly regarded Georgians, inhabitants of the Caucasus, as the most handsome people! But this pronouncement, like so many Lawrence made about different races and tribes of man, was actually based on rather uncritical acceptance of comments made by various travellers, for his own knowledge of other races and their potentialities was distinctly second-hand. His anthropological work was not based on original research, but did bring usefully and logically together information from a variety of sources.

Literary inspiration

Among Lawrence's patients were Percy Shelley and his mistress, and later second wife, Mary Godwin, daughter of the radicals William Godwin and Mary Wollstonecraft. Shelley seems to have known Lawrence since his own abortive attempt — after being

expelled from Oxford for 'atheism' — to himself become a surgeon at St Bartholomew's in 1811, "walking the wards", as he put it. Already that summer his ideas on the nature of life are expressed more like Lawrence's than previously. From then on Shelley's poetry and prose contain many references to the debate on 'vitalism', with the poet clearly influenced by Lawrence. In 1812 Godwin met Lawrence through a couple called Newton — one of whom was the author of the vegetarian tract *Return to Nature* — and it seems that around this time Lawrence, like others of this circle of friends, was a vegetarian himself. By 1818 Lawrence was saying in his lectures that man is naturally omnivorous, and — in an admirably modern way — that to decide whether vegetarian diet was best it would be necessary to conduct a properly monitored scientific experiment for several years (Lawrence 1819, 222).

The Shelleys consulted Lawrence when Mary was pregnant in 1814 and the following spring when Shelley had symptoms of tuberculosis. Later, in 1815, Shelley went to him with abdominal trouble, and wrote to a friend that his health had been considerably improved under Lawrence's care (Jones 1964, 429). Shelley consulted Lawrence again two years later; Mary wrote: "… ah! my love you cannot guess how wretched it was to see your languor and encreasing [*sic*] illness. I now say to myself perhaps he is better — but then I watched you every moment & every moment was full of pain both to you and to me — write my love, a long account of what Lawrence says — I shall be very anxious until I hear …" (quoted in Bennett 1980, 41). What Lawrence recommended, apparently, was to stop writing poetry for a time! He also suggested that a warmer climate might help; the house where they were living was cold and damp. And in fact the Shelleys went to Italy soon after this advice was given.

The year before, Mary had begun writing the novel that has made her as celebrated as her husband: *Frankenstein*. A strong case has been made that it was originally planned as "a short satire of Abernethy's position, exposing it as nonsense. The being animated by the infusion of a 'spark', apparently of electricity, is not human but a grotesque distortion of our form, which the humans in the story cannot acknowledge" (Hetherington 1989, 3). Perhaps it is true, as Butler suggests, that Lawrence "could have guided the couple's reading in the physical sciences from the time they became partners in 1814 to the moment of the novel's emergence, some four years later" (Butler, 1994, xvi). It seems almost certain that the novel, in its original form, supports Lawrence's dismissal of 'vitalism' in favour of life as a result of physical organisation. "Frankenstein the blundering experimenter, still working with superseded notions, shadows the intellectual position of Abernethy, who proposes that the superadded life-element is analogous to electricity. Lawrence's sceptical commentary on that position finds its echo in Mary Shelley's equally detached, serio-comic representation" (Butler 1994, xvi–xxi; for Lawrence and the Shelleys see also Crook and Guiton 1986, Luke 1965 [corrections in Cameron and Reiman, 1961–73, V 144], Mishra 1994, Ruston 2005a and 2005b, and Temkin 1963).

Joining the establishment

The Lancet was founded in 1823 as a crusading journal to improve the medical profession; Lawrence attended night-time editorial meetings with the founding editor Thomas Wakley, the outspoken radical journalist William Cobbett, and a libel lawyer, and himself wrote many early editorials. As late as 1826 Lawrence was still attacking the oligarchy that ran the Royal College, chairing mass meetings of up to 1,200 people at the Freemasons Tavern (where the Geological Society had been founded nearly 20 years before). With others he called for "the remedying of abuses in the Royal College" (*The Times* 1826, February 20, 3 and March 6, 3). Parliament was petitioned the following year, and Abernethy, who was president of the Royal College, took steps to improve matters, including access to the Hunterian Museum and Library, previously limited to those, like the student Lawrence, who had influential patrons.

In 1828, however, Lawrence joined 'the establishment' that he had outraged and "so much abused" (Anon. 1867a). There was suspicion of him at first; he was only elected onto the Council of the Royal College of Surgeons by one vote. But he was partially reconciled with Abernethy, whose support was decisive in his unanimous re-election the next year. When Wakley, his old *Lancet* colleague, who had consistently supported him for the last 10 years, turned up to protest, Lawrence helped manhandle him out of the room. "Wakley", says Adrian Desmond, the historian of medical changes at the time, "viewed his apostasy with 'intense repugnance' ". It became more painful in 1832 because Lawrence was now mixing "in friendly combination with those very men who are prosecuting inimically his former friends" (Desmond 1989, 257). There are only slight indications that he regretted what the radicals thought was 'apostasy' — turning away not only from bold scientific speculation but also from the true faith of a properly reformed organisation for the surgical profession. In 1830 Lawrence wrote to William Hone, by now less of the radical publisher and more an antiquarian bookseller: "I beg you to accept the accompanying copy of my lectures, and to assure you that although I thought it expedient to withdraw this work from circulation, no considerations of expediency would ever induce me to shun the appearance of intimacy with one whom I respect so highly for talent and the most important public services, as well as for the profession of much greater courage in these matters than falls to the lot of Yours very faithfully W. Lawrence" (Lawrence 1830).

A remarkable article in 1854 shows how controversial a figure he still was, not now for being as "in youth the free-thinking, the bold, the defiant, the render of musty parchments, the denouncer of old abuses, the sneerer at ancient reverence", but for being "in later life, the discreet, the conformable and reserved, the admirer of every thing past except his own career, the sustainer of law, to whom all change is destruction, all novelty anathema, who rolls himself up comfortably in the mantle of his own esteem, and warms himself at the flames of sycophancy and adulation" (Anon. 1854, 191).

The editors of *The Lancet*, furious at his desertion of the cause of radical reform of the profession even 40 years later, included in its otherwise complimentary obituary in 1867: "The Council feared him, and elected him to their body. From that moment Mr Lawrence became a conservative and an obstructive, and maintained that character to the close of his life. He not only deserted his former friends, but lost no opportunity of reviling them … During the long period that he was a member of the Council and of the Court of Examiners [he] resolutely and consistently opposed every attempt that was made to improve the education and the status of the surgeon in general practice" (Anon. 1867b, 45).

It is easy to think that Lawrence's desertion of the cause of reform of his profession is far less excusable than his abandonment of scientific speculation. But Desmond strikes a balance: "Educated to rank and privileges, he was caught between the iniquities of the Old Corruption and the career dangers of a republican remedy. Radicals recalled his 'quiet sneering smile', which they came to see as concealing a disingenuous nature. But democrats in general practice and in the press could afford to be uncompromising with so much less to lose. As a hospital surgeon Lawrence appreciated the value of political expediency, and he continued to function as a moderate reformer on the council … Lawrence's case left no one in any doubt of the value of compromise" (Desmond 1989, 258).

In 1844 the King of Saxony was in London accompanied by his physician, Carl Gustav Carus, the physiologist and painter whose concept of the vertebrate archetype influenced Owen and Darwin, and who was the first to develop the notion of the unconscious. Carus made "a visit to Mr Lawrence, author of a work on the 'Physiology of Man', which had interested me much some years ago, but which had rendered the author obnoxious to the clergy, because he had endeavoured to penetrate a little more deeply into the relation between the conscious and unconscious life of the soul (generally, but unscientifically, denominated soul and body). He appears to have allowed himself to be frightened by this, and is now merely a practising surgeon, who keeps his Sunday in the old English fashion, and has let physiology and psychology alone for the present. I found him a rather dry, but honest man" (Carus 1846, 88).

Looking back in 1860 on his controversies with Abernethy, Lawrence wrote of "events which though important at the time of occurrence have long ceased to occupy my thoughts" (quoted in Thornton 1953, 136). Lawrence seems to have recorded only one comment for the rest of his life on the great topics of evolution and man's nature. This was not on *Origin of Species* or on the immediate subsequent debate, but in 1862 when T. H. Huxley, who had just become the Hunterian Professor at the Royal College of Surgeons, boldly showed him the proofs of his forthcoming Evidence as to *Man's Place in Nature*. The proofs had also gone to Joseph Hooker and Charles Lyell, who had both been impressed. Lyell wanted him to tone down his 'dangerous sheets' and 'naughty' phrases; Lawrence, however, advised him not to publish at all, to protect his reputation (Desmond 1994, 307–8, 421 n. 35).

Worldly success

I think Lawrence's transformation from radical reformer to pillar of the establishment and from advanced thinker to silent observer of the next 50 years' progress was connected with his marriage. He was 45 when he married Louisa Senior, the socially ambitious 25-year-old daughter of a Mayfair haberdasher who was successfully becoming a Buckinghamshire squire, and that was in the same year, 1828, that he joined the Council of the Royal College. There is a faint suggestion of the final situation of Dr Lydgate in *Middlemarch*, set in precisely this period, where the keen young physician, ambitious to make discoveries that will benefit mankind, settles in the end for a fashionable London practice because of his wife's social ambitions. George Eliot would certainly have known of the Lawrence drama of 1819–28. Louisa's success in building a social position as a pioneer horticulturist is a story in itself.

Early in 1867 Thomas Huxley sent Lawrence a copy of his latest work and he replied "in your modest book '*indocti discant, ament meminisse periti!*" [the ignorant may learn and the experts rejoice to be reminded] (Huxley 1903, 283). Lawrence died a few weeks later, just before his 84th birthday. After having refused honours for many years — perhaps to punish himself for his abjuration of speculation and reform — he accepted a baronetcy in the last months of his life, possibly in the fruitless hope that it would help his son marry an aristocrat. Curiously, that son presided in 1899, as President of the Royal Horticultural Society, over what is now recognised as the first international conference on genetics.

William Lawrence, aged 80.

References and sources

Anon. 1820 *The Radical Triumvirate; or Infidel Paine, Lord Byron and Surgeon Lawrence, colleaguing with the Patriotic Radicals to emancipate mankind from all laws, human and divine* ... A letter to John Bull, from an Oxonian Resident in London. London, no publisher given

Anon. 1854 *The Medical Circular and General Medical Advertiser*, 191ff

Anon. 1867a Obituary. *Brit Med J*, July 13

Anon. 1867b Obituary, *The Lancet*, 13 July, 44–6

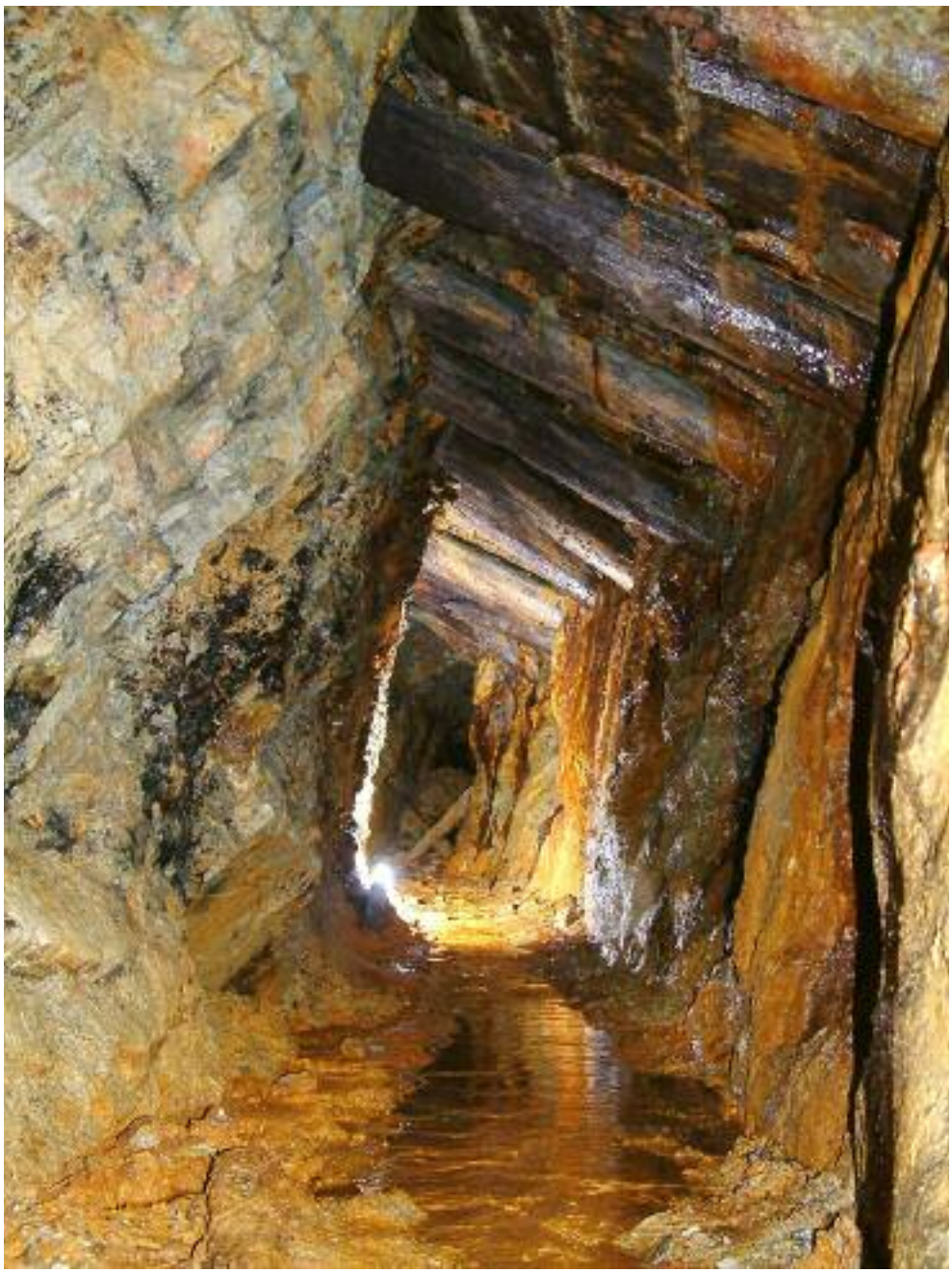
Bennett, Betty T. ed 1980 *The Letters of Mary Wollstonecraft Shelley*. Baltimore and London: Johns Hopkins U P

Blumenbach, Johann Friedrich 1807 (trans. William Lawrence) *A Short System of Comparative Anatomy*. London: Longman and Co.

Butler, Marilyn 1994 *Frankenstein*: 1818 Text. Oxford U P

Winner for Geological Landscape category: Jenny Forrest (Walton Hall Branch)
El Golfo, Lanzarote, Canary Islands; photograph © Jenny Forrest
This Pleistocene tuff cone of El Golfo on Lanzarote, was formed by a hydrovolcanic explosion as the volcano erupted into shallow seas. The resulting maar owes its colour to colonisation by green algae. The walls of the crater show the weathered remains of the tuff cone; bright colours of palagonite are revealed as the greyish veneer is eroded. The red deposits in the foreground are from the ash fall produced as the cone entered a later Strombolian phase of eruption.

Winner for Geological Feature or Structure category: Tony Martyr (West Midlands Branch)
Faulted Boulder, Butt of Lewis; photograph © Tony Martyr
The photograph was taken near the Butt of Lewis MR: NB 524659. There is some difficulty with exact identification and I invite comments from fellow OUGS Mmembers! On geological maps the small bay at this location is marked as being on a boundary between the metasedimentary rocks of the Lewisian Complex (that form most of the tip of Lewis) and a band of Scourian gneiss. I was looking for this junction, but was hindered by an incoming tide, when I noticed this rock (length 1.5m), which had clearly come from the adjoining landward cliff. The fault was obvious, but I was interested in the glass-like in-fill of the fault line, which I took to be pseudotachylite. I would class the rock as a mylonite, which then suffered brittle fracture, but I have no idea which of the two rock types described on the map it is — to me it was a mystery and had a very interesting history. Perhaps fellow OUGS Members can help with an identification?



Winner for Industrial Geology category: Chris Popham (South West Branch)
Adit Level, South Crebor Mine, Tavy Valley, Devon; photograph © Chris Popham

The Tamar and Tavy valleys in Devon were worked extensively in the 1800s for a variety of metalliferrous minerals. South Crebor (a.k.a. East Wheal Russell), south of Tavistock, was worked primarily for copper, but later also for arsenic, as were many other mines in the south-west. The portal to this adit lies at river level, to serve principally as a drain for the mine. It does, however, follow a lode, and although this had only low economic value there were, in places, packets of workable ore.

The method used here is that of overhand 'stoping': the miners pulled down the roof of the adit, creating a long, narrow void — a stope the width of the lode or just wide enough to permit working. When the roof of the working space was no longer within reach, timbers ('stulls'), were fitted across the stope and planked over, and work resumed on the 'level' platform thus made. In this way a stope could reach heights of many tens of meters, with multiple levels.

The shallow dipping beds of the pale country rock ('killas') can be made out in the hanging (left-hand) wall of this adit in sharp contrast to the near-vertical dip of the footwall. It was in this fault zone that the circulating hydrothermal waters deposited the mineral lode, which is principally composed of stringers of small quartz crystals encapsulating fault breccia; in places this is highly altered, forming a chloritic clay. Metasomatism has significantly enriched the lode in places, replacing the copper sulphide 'chalcopyrite' ore with copper oxides, carbonates and, rarely, with native copper, making this a fine example of this geological process.

Winner for AGM Delegates' Popular Vote category: Bob Morley (East Scotland Branch)
Cuernos del Paine, Parque Nacional Torres del Paine, Cordillera del Paine, southern Chilean Patagonia; photograph © Bob Morley
A light coloured granitic laccolith intruded in three chemically distinct pulses about 12.5Ma ago between the black turbidites of the Cerro Toro formation (on top), metamorphosing them, and the gabbro and diorite of the Paine Mafic Complex (below). The landscape has been sculpted by glaciation to produce the spectacular Cuernos (Horns) del Paine.

Cameron K. N. and Reiman, D. H. 1961–73 *Shelley and His Circle*, 1773–1822 (6 vols). Cambridge MA: Harvard U P

Carlile, Richard 1821 *Address to the Men of Science; calling upon them to stand forward and vindicate the truth from the foul grasp and persecution of superstition*. London: R. Carlile

Carus, C. G. 1846 (trans. S. C. Davison) *The King of Saxony's Journey through England and Scotland in the Year 1844*. London, Chapman and Hall

Chance, Burton 1926 'Sir William Lawrence in relation to medical education …'. *Annals Med Hist* **8**, 270–9

Crook N. and Guiton, D. 1986 *Shelley's Venomed Malady*. Cambridge U P

Darlington, C. D. 1959 *Darwin's Place in History*. Oxford: Blackwell

Desmond, Adrian 1989 *The Politics of Evolution*. U Chicago P

Desmond, Adrian 1994 *Huxley: The Devil's Disciple*. London: Michael Joseph

Hetherington, Naomi 1997 'Creator and created in Mary Shelley's *Frankenstein'. Keats-Shelley Rev* **11**, 1–39

Holmes, Richard 2008 *The Age of Wonder*. London: HarperPress

Huxley, Leonard ed. 1903 *Life and Letters of T. H. Huxley*. London: Macmillan Jacyna, L. S. in *Oxford DNB*

Jones, Frederick L. ed. 1964 *The Letters of Percy Bysshe Shelley*. Oxford: Clarendon Press

Lawrence, William 1816 *An Introduction to Comparative Anatomy and Physiology, being the two introductory lectures delivered at the Royal College of Surgeons*. London, no publisher given

Lawrence, William 1819 *Lectures on Physiology, Zoology, and the Natural History of Man*. London: J. Callow

Lawrence, William 1830 letter to William Hone BM. Add mss 40.12, f 171–2

LeFanu, W. R. 1957 *Annals of the Royal College of Surgeons of England* **25**, 201–2

Luke Jr, Hugh L. 1965 'Sir William Lawrence: Physician to Shelley and Mary'. *Papers on English Language and Literature* **1**, 141–52

Lewis, C. L. E. and Knell, S. J. (eds) 2009 *The Making of the Geological Society of London*. London: Geological Society Special Publications 317

Mishra, Vijay 1994 *The Gothic Sublime*. Albany: State U New York P

Mudford, Peter G. 1968 'William Lawrence and *The Natural History of Man*'. *J Hist Ideas* **29**, 430–6

Paget, Stephen (ed) 1901 *Memoirs and Letters of Sir James Paget*. London: Longmans, Green

Philostratus, pseud. [i.e. Thomas Forster] 1823 *Somatopsychonoologia: showing that the proofs of body, life and mind, considered as distinct essences, cannot be deduced from physiology, but depend on a distinct sort of evidence. Being an examination of the controversy concerning life carried on by MM. Laurence* [sic]*, Abernethy, Rennell, and others*. London: no publisher given

Plarr, Victor 1930 *Lives of the Fellows of the Royal College of Surgeons of England*. [volume one, on-line, no page refs.]

Quarterly Review 1820 **XXII**, 1–34

Ruston, Sharon 2005a *Shelley and Vitality*. Basingstoke: Palgrave Macmillan

Ruston, Sharon 2005b 'Natural enemies in science, as well as in politics: Romanticism and scientific conflict'. *Romanticism* **11**, 70–83

Savory, W. S. 1868 Obituary in *St Bartholomew's Hospital Reports*, **IV** 1–18

Temkin, Owsei 1963 'Basic science, medicine, and the Romantic era". *Bull Hist Med* **37**, 97–129

The Times 1822, 25 March and 27 March *Law Report*, Court of Chancery

The Times 1826, February 20 and March 6

The Times 1867, 10 July

Thornton, John L. 1953 *John Abernethy*. London: privately printed

Wells, Kentwood D. 1971 'Sir William Lawrence (1783–1867): a study of pre-Darwinian ideas on heredity and variation'. *J Hist Biol* **4**, 319–61

Author

Philip Clark, MA Oxon (honours, schools of Modern History and Theology), BSc Open (Natural Sciences with Earth Sciences) and OU Dip in Mus. He is a great-great-grandson of William Lawrence.

Book review

Thomas, Jo 2008 *Dorset Stone*. The Dovecote Press (ISBN 978-1-90434-963-1; paperback, 128pp; £17.95)

This well-illustrated book is the result of many years of painstaking research. Using knowledge gained in a first class honours Geology and Science Degree from the OU, Thomas set about collecting data from her local area. This became so interesting that her research area eventually covered the whole of Dorset.

The first chapter gives an overview of the subject, the use of building stones in Dorset, the geological history of those stones and the history of their quarrying and transport. This is interesting enough to whet your appetite for what follows.

There then follows the main subject of the book: eight chapters dealing in detail with the stones. Starting at the bottom of the geological sequence in Dorset, the Lias, Thomas works her way up the sequence through the Inferior Oolite, the Forest Marble and Cornbrash, the Corallian Limestones, the Portland Freestone, the Purbeck Limestones, the Cretaceous rocks, and finishes with the Tertiary Heathstone.

Each chapter starts with a description of the depositional environment of the stone in question, the geological history and a description of the beds themselves. The use of each stone is described and examples quoted, accompanied by superb photographs of the buildings themselves and often a close-up of the stones. A map of the outcrops, the quarries and also sometimes the parishes is also included.

Not content with just describing buildings, Thomas then embarks on a fascinating chapter on Stone Bridges of the Stour Valley. Again, each bridge is described in great detail, attention being paid to the specific use of each type of stone used, whether or not it was suitable for underwater use or otherwise. Dorset bridges are famous and Thomas's superb photographs do them justice.

The final chapter covers brick-making, a suitable topic, as there are numerous clay outcrops in the area covered. Some buildings are a mixture of stone and brick, used to great advantage in appearance.

Finally, there is a table of Building Stone by Parish, enabling the reader to locate which stone is prevalent in each location; OS references are given.

Even if you do not live in Dorset and have never visited it, this book is fascinating and well worth a read — I certainly have a copy on my bookshelf.

— Jane Clarke, MPhil Open

Book review

Trewin, Nigel and Hurst, Andrew (eds) 2009 *Excursion Guide to the Geology of East Sutherland and Caithness* (2 edn). Dunedin Press (ISBN 978-1-90671-601-1; paperback, 184pp; £14.99)

The first edition of this book, now out of print, was published in 1983 according to the frontispiece, or in 1993, according to the editorial introduction!

It is slightly taller and also slightly narrower than A5 in format. Its editors assume "some previous knowledge of geology" — actually a great deal. There is no glossary and there were some words, e.g. 'poikilotopic', the meaning of which I did not know. There are many examples of poor English and some typographical errors. With seven pages of references — surely excessive for a field guide — this book seems to be aimed more at PhD students than at those visiting for a day.

The text covers the area east of Kirtomy Bay on the north coast and north of Embo on the east coast: the whole of square ND (that is, on the mainland) plus the eastern quarter of square NC and a very small area in square NH of the National Grid. The sketch map of the geology of the area is simple and comprehensible and gives a good basis for understanding each area covered by the excursions. I was glad to see that the Timespan Heritage Centre exhibition in Helmsdale, which I had found fascinating, was recommended.

Try not to be put off (as I was) by the first chapter, which gives a geological history of the area. At 35 pages, I found the amount of detail much more than sufficient. It was difficult to follow the main sequence of events because of all the minor variations discussed, with innumerable references to differing interpretive opinions — which would be less intrusive if simply numbered.

I thought this book far too academic for a field guide (in comparison, for example, with a field guide such as *Northumbrian Rocks and Landscap*e edited by Colin Scrutton; 1995, Yorkshire Geological Society). There is a clear stratigraphic column with references to the excursions in which each formation is found. Apart from the Basement, which is described as pre-Devonian, the rocks exposed are Devonian, Permo-triassic and Jurassic.

The five pages of the 'Excursion Planner' give useful details of what each of the six excursions covers, the time required and any tidal constraints.

I have not been back to the area covered in this guide since following 'The Highland Geology Trail', which goes around it, two years ago, and having previously been on an OUGS field trip to the NE, so I have not tested the excursion instructions in the field. However, they appear to be adequate, with notes where confusion is likely to arise from changes in road configurations. The instructions are mixed with the description of the rocks, i.e. in the same paragraph and font, which makes it more likely that some necessary instruction or description will be missed. The actual descriptions seem to be clear and reasonably concise, although the frequent references are intrusive.

Conclusion: An essential guide for those who decide to visit the area. It is comprehensive and fairly easy to follow. I slowly warmed to it (and revised what I had written!) once I had got past the most off-putting introduction and into the excursion details. I would certainly get a copy if I were to return to the area.

— Zoë Gardner

Geomorphological features of the Carboniferous Limestone on the coast of South Pembrokeshire

John Downes

Introduction

The south coast of Pembrokeshire exhibits some spectacular geomorphological features. In order to appreciate the variety of landforms it is necessary to walk the coast path between Stack Rocks [SR925946] and St Govan's Head [SR975927], a distance of about 5km (Fig. 1). This beautiful stretch of coastline lies within the Castlemartin Firing Range and access is limited on weekdays, but the path is usually open at the weekends. It is advisable to check accessibility with the Ministry of Defence (MOD) by telephoning 01646 662367 for a recorded message on the range opening times. There are car parks at both ends of the walk and the Coastal Cruiser bus service operates during the tourist season calling at both car parks.

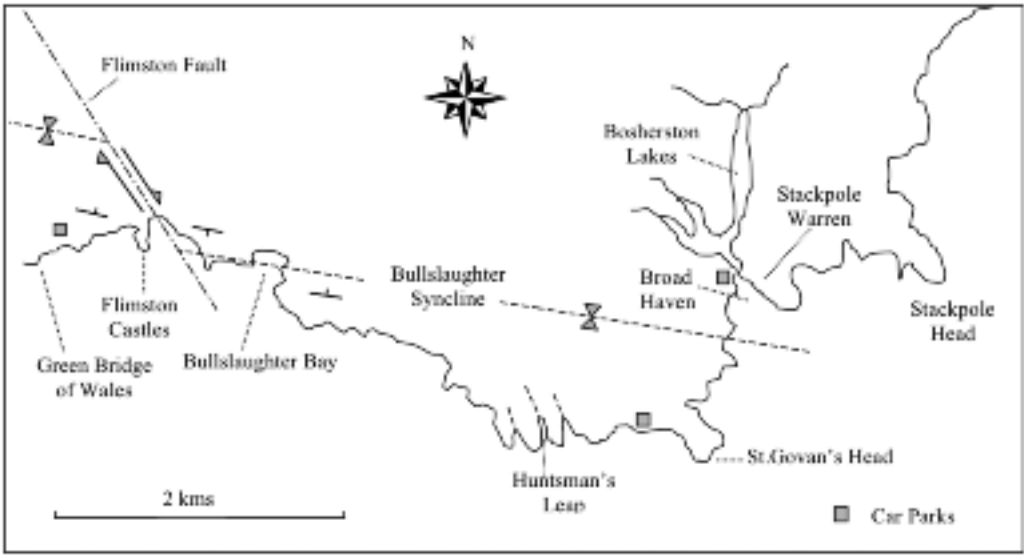


Figure 1 The limestone coast of South Pembrokeshire.

1. Arches, stacks and blow-holes

Probably the most photographed rock formation on the coast is the Green Bridge of Wales [SR 925944], a natural arch cut into the well-bedded Pen-y-Holt Limestone (Arundian Stage of the Dinantian) that is dipping gently northwards (Fig. 2, *overleaf, top*). The arch has been created by the coalescence of caves on opposite sides of a small headland. Eventually the main arch will collapse and leave two stacks similar to the nearby Elegug Stacks, which provide superb examples of sea stacks left standing as the cliff line recedes under constant attack from the waves. Elegug is the Welsh name for the guillemot and there are large numbers of guillemots, fulmars and gannets nesting on these cliffs and stacks during the summer breeding season.

Although the Green Bridge is visited by thousands of people every year, only a small proportion of them walk eastwards along the coast path to explore the scenic delights of the coastline. About 750m beyond Stack Rocks is the promontory known as Flimston Castles [SR930945], on which stand the ramparts of an Iron Age fort. This locality is riddled with caves and arches but is dominated by the deep shaft called the Devil's Cauldron. This may be described as a blow-hole, as the sea 'boils' and surges up through it in stormy weather. Take great care when exploring here, as there are 50m cliffs on either side of the pathway in some places. It has been suggested that the Devil's Cauldron are the remains of a former swallow hole in the limestone,which has since been broken into by marine erosion (see section 4).

2. Cliff morphology

Flimston Bay lies on the east side of Flimston Castles, where the Flimston Fault reaches the coast. The fault shatter zone can easily be recognised by the orange-coloured gash breccias in the cliffs (see section 3). This is a major wrench fault, produced by the Variscan earth movements, that runs NW–SE across the Castlemartin Peninsula from Freshwater West. This type of fault involves the horizontal movement of the land in opposite directions on either side of the fault. The Flimston Fault has moved dextrally (to the right as you are looking across the fault) and offsets the rocks on the east side of the fault to the south-east. As a result of this movement, the strata to the east belong to higher zones of the Carboniferous Limestone. Hence the Stackpole Limestone (Holkarian Stage) to the west is brought up against the younger Crickmail Limestone (Asbian Stage) to the east. The fault also affects the dip of the limestone beds because the E–W axis of the Bullslaughter syncline is offset, so that the beds are dipping northward (inland) to the west of the fault and southward (seaward) to the east of the fault (Fig.1). Thus where the limestone beds dip gently inland they produce steep, sometimes overhanging cliffs; by contrast, where the dip is seaward, the cliff profile is often stepped and less steep. Nevertheless, rockslides occur along the inclined bedding planes under the influence of gravity, as seen around St Govan's Head (Fig. 3, *overleaf, bottom*). The large joints in the massively bedded limestone also facilitate rock falls producing enormous blocks that crash down onto the wave-cut platform at the foot of the cliffs.

The cliffs are also cut by numerous small faults, particularly between Saddle Head [SR958928] and St Govan's Head. The sea

OUGS Journal 31 (1–2) 2010, 29–32
© OUGS ISSN 0143-9472

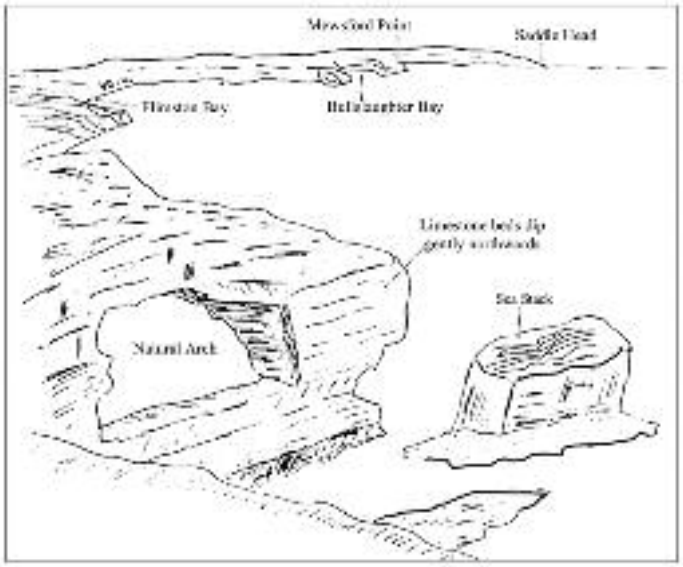


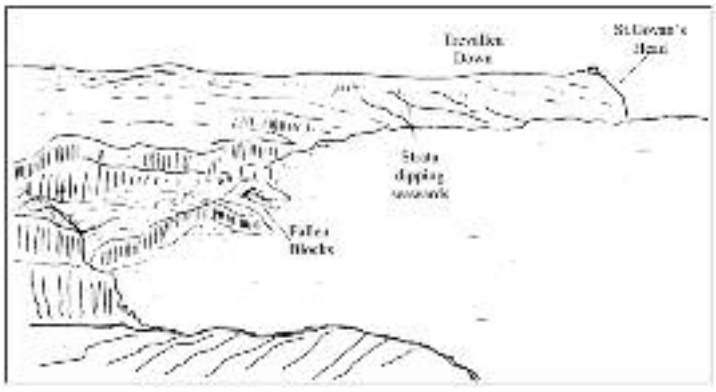
Figure 2 The green bridge of Wales.

erodes the limestone along the faults that are aligned at right angles to the cliff line, thus producing steep, narrow inlets known as 'geos'. The most famous of these geos is Huntsman's Leap (Fig. 4, *opposite, top left*), a 30m deep vertical chasm that is only a few metres wide at its entrance; narrow enough to be jumped by a galloping horse! However, this is not a recommended practice, as the drop to the sea below is more than 40m. The next inlet to the west is the Devil's Barn, which includes two blow-holes and a natural arch; and when these features eventually collapse, a new geo will be formed.

3. Gash breccias

These are pockets of sandy clay containing angular clasts of limestone that are associated with areas of tectonic instability. They appear to be unique to the limestone coast of South Pembrokeshire and their origin is somewhat enigmatic. Strictly speaking, they are not geomorphological features, as they are deposits that probably date back to Triassic times. However, their origin may well be due to geomorphological processes in that they could have been formed when limestone caverns collapsed and became filled with boulders and sandy sediment during flash floods in Triassic times. In other words, their formation could be related to karstic weathering processes in post-Dinantian times. Alternatively, the brecciation may result from intense brittle fracturing during the Variscan orogeny, since these deposits are often found in association with major faults (e.g. Flimston fault) or near fold axes (e.g. Bullslaughter Bay syncline). Chemical weathering of the limestone could also have provided the residual clay matrix as surface waters percolated down through the shattered rocks forming in-filled pockets and pipes. One of the best places to examine a gash breccia deposit is on the north-east side of Bullslaughter Bay (Fig. 5, *opposite, top right*), where access to the beach is possible down a narrow gully. At the base of the gully the gash breccia forms the cliff face, which is stained by iron minerals and contains a melange of large boulders and smaller clasts set in a sandy clay matrix. The deposit is aligned parallel to the E–W axis of the Bullslaughter syncline, which crosses the bay.

Figure 3 View looking eastward to St Govan's Head.



4. Karstic features

Probably the best area in which to look at karstic weathering landforms is Longstone Down, immediately to the east of Flimston Bay. Here the limestone cliff top surface can be explored in a cliff top zone some 500m wide. The MoD has clearly marked the limit beyond which it is dangerous to proceed for fear of unexploded ordnance! Longstone Down is an undulating limestone plateau that is part of a Pliocene marine planation surface that extends across much of Pembrokeshire from St David's in the NW to Tenby in the SE.

On Longstone Down, this bevelled surface cuts across Crickmail Limestone, dipping seawards at about 60º as the northern limb of the Bullslaughter syncline. The surface is thought to be of Neogene age since it truncates a pocket of Oligocene pipe clays near Flimston. Interestingly, this clay was last worked in the 1870s when it was used for mixing with coal dust to make 'culm' balls for domestic heating and also in the manufacture of silica bricks. The clays are interbedded with sands and gravels and are preserved in depressions up to 14m deep. It is possible that they occupy solution hollows that were already established as palaeokarstic features in Oligocene times. Unfortunately the exact location of the disused clay pits is now out of bounds within the MoD firing range.

The limestone surface is only partially exposed on Longstone Down as much of it is covered with a deposit of terra rossa that in turn supports a profuse flora of grasses, herbs and wild flowers. This red, clayey soil is produced by the chemical weathering of the limestone when rainwater removes the calcium carbonate in solution, leaving an insoluble iron-rich residual deposit.

There are numerous closed depressions or solution hollows in the limestone surface that vary from *c.* 5m to 15m in diameter. These depressions appear to be in-filled swallow holes or 'dolines' (or possibly incipient forms), often developed at the intersection of major joints that have been widened by solution. In some cases it may be that the depressions are due to collapse of the roof of underground caverns. Along the cliff line there are examples of dolines that have been breached by coastal erosion, so that here they form a semi-conical shape open to the sea on one side. There is a particularly good example of a deep shaft with tufa-lined walls that has been breached by the sea at the Devil's Cauldron on the west side of the Flimston promontory.

The formation of limestone pavements is related to the inclination the beds. The best-developed pavements are found where the beds are horizontal, as in the Yorkshire Pennines. When the dip approaches 45º the pavement surface becomes stepped as the edge of each bed forms a riser. This is well seen along the margin of the cliffs on Longstone Down, where the grikes

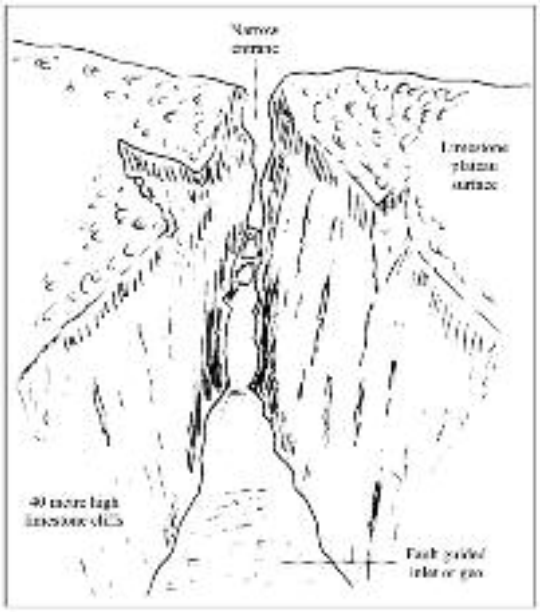


Figure 4 View of Huntsman's Leap, looking seaward.

(fissures) tend to follow the inclined bedding planes and the limestone clints (blocks) stand proud. The weathered surface of the clints is often pitted with solution runnels (grooves) and small solution cavities.

5. Glacial erratic

The earliest known glaciation of South West Wales occurred at some time before the Ipswichian Stage (128,000–122,000 BP), possibly starting *c.* 140,000 BP when Irish Sea ice advanced south-eastward toward Pembrokeshire, overriding Mynydd Preseli and sweeping over the lowlands of the south coast. Local Welsh ice moving south-east down the Teifi and Tywi valleys would also have contributed to the overall depth of ice cover. The limestone surface of South Pembrokeshire is littered with boulders and pebbles that have been carried by ice from as far afield as North Wales and Southern Scotland. You can examine a collection of erratics in the graveyard of Flimston Chapel [SR924956] on the Castlemartin Peninsula. They were collected from the surrounding area by a Colonel Lambton in the early 20th century and some have even been used as gravestones! The erratics include a gabbro from St David's Head and a dolerite from Mynydd Preseli.

6. Coastal geomorphology from Broad Haven to Stackpole Head

For anyone wishing to explore the limestone coast farther east of St Govan's Head, it is worth visiting Broad Haven, near Bosherston, where there is a National Trust car park at SR976938. Alternatively walk the coast path from St Govan's Head car park to Broad Haven. Cross the beach to the limestone outcrop on the north-east side of the bay at SR980941, where the beds are dipping southward and are planed off about 3m above the high water mark. This platform is covered by the remnants of a raised beach deposit of rounded pebbles and cobbles set in a sandy matrix, with patches of cemented shelly deposits in places (Fig. 6). However, the raised beach platform is much dissected and eroded by gullies, but it grades upwards into a layer of cemented Blocky Head composed of limestone

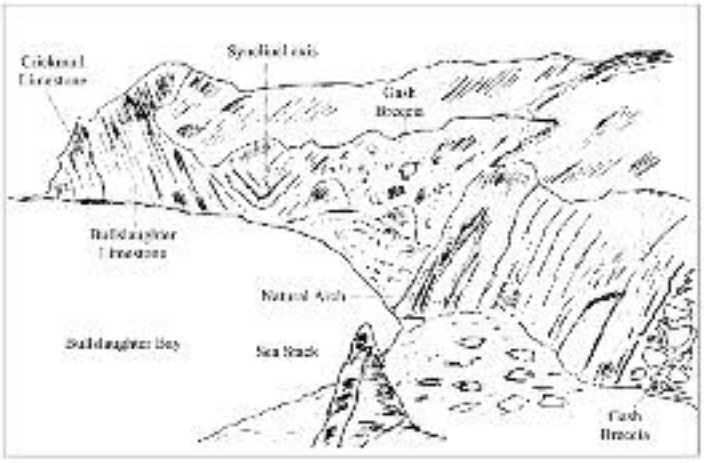


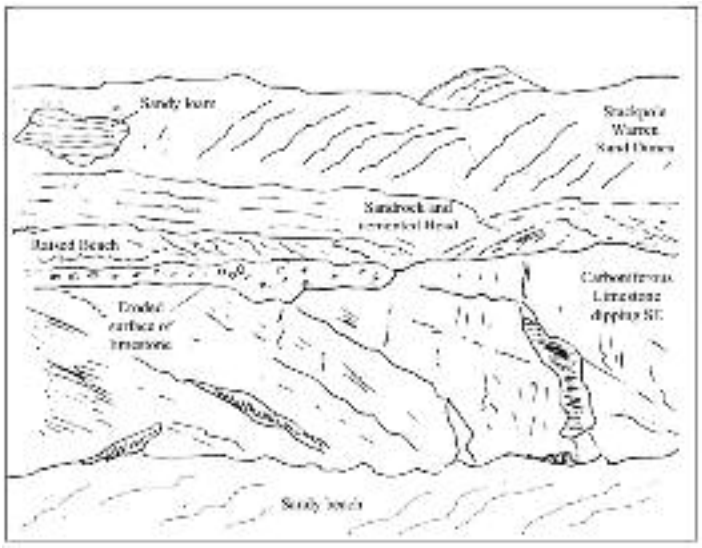
Figure 5 View westward across Bullslaughter Bay.

clasts up to 200mm across. There are also patches of sand-rock up to 2m thick that appear to be incorporated into the head deposit. At the top of the section there are exposures of sandy loam and blown sand that form extensive dunes around Broad Haven. The lack of till at this locality and the presence of Blocky Head suggest that the area experienced periglacial conditions when it was located south of the ice front during the Late Devensian.

While standing on the raised beach, look across Broad Haven to the sand dunes that extend around the head of the bay. These ridges of sand are formed where there is a wide foreshore that dries out between the tides. Onshore winds blow the dry sand inland so that the resulting dunes tend to migrate landward until anchored by vegetation such as marram grass. Stackpole Warren is a zone of wind-blown sand more than a kilometre wide that extends from Broad Haven across to Barafundle Bay. The sand dunes mask the underlying limestone plateau surface.

Broad Haven forms the drainage outlet from what are known as the Bosherston Lakes (also called the Lily Ponds) that were established by the owners of the Stackpole Estate as an ornamental landscape feature in the mid-18th century. This man-made landscape of freshwater lakes with dams and sluice gates was created from the lower reaches of the Broad Haven valleys. Today the National Trust and the Countryside Council for Wales

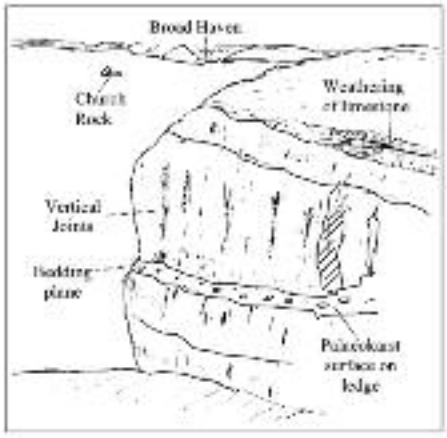
Figure 6 Raised beach at Broad Haven (Bosherston).



manage the area as a National Nature Reserve. Yet this semi-natural environment has been created from a geomorphological feature left over from the late Devensian, *c*. 10,000 years ago. The valleys were flooded as sea level rose during the Flandrian marine transgression following the melting of the ice sheets. Deciduous woodlands and swamp gradually developed around the tidal creeks and salt marsh backed by sand dunes must have covered much of the Broad Haven estuary.

Climb up the coastal path from Broad Haven beach and follow the cliff-top path leading to Stackpole Head [SR995942]. En route you will pass a huge blow-hole (*c*. 50m in diameter) called Sandy Hole [SR984943] and the deep, faulted inlet or geo of Ramming Hole [SR987945]. After passing Mowingword Bay, where there is an impressive sea stack, continue to the extremity of the headland. The massive limestone beds at Stackpole Head are almost horizontal and where the limestone is exposed on the plateau surface there is much evidence of present-day solution weathering. However, if you look carefully at the bedding plane forming a prominent ledge about a third of the way up the cliff face you will see a pot-holed surface (Fig. 7). This is a palaeokarst surface that can be traced around the cliffs for about 400m. It has been subjected to karstic weathering in Lower Carboniferous times during a pause in deposition when the limestone was exposed as a land area. Looking down to the ledge from the top of the cliff, you can see that it is extensively pot-holed; and with the use of binoculars it is possible to observe that the pot holes are filled with orange or buff clay. This clay represents a palaeosol or fossil soil formed as a result of the chemical weathering of the palaeokarst surface when it was exposed to sub-aerial denudation.

Figure 7 View toward the west from Stackpole Head.



Sources consulted

Dixon, E. E. L. 1921 *The Geology of the South Wales Coalfield. Part XIII. The Country around Pembroke and Tenby*. Mem Geol Soc Great Britain. London: HMSO.

George, G.T. 2008 *The Geology of South Wale*s. www.geoserv.co.uk 144–153

Howells, S. 1999 *Stackpole Estate*. National Trust

Haycock, R. and Ellis, R. 2002 *Bosherston Lakes*. National Trust and CCW

John, B. S. 1978 'Valiant cliffs of Pembrokeshire'. *Geogr Mag* **50**, 467–70

May, V. J. 2003 'South Pembroke cliffs', *in* May, V. J. and Hansom, J. D. *Coastal Geomorphology of Great Britain*. Geol Cons Rev Ser **28**. Peterborough: Nature Conservancy Council

Sparks, B. W. 1979 *Rocks and Relief.* London: Longman, 203–45

Steers, J. A. 1964 *The Coastline of England and Wales*. Cambridge U P, 155–66

Thomas, T. M. 1971 'Gash breccias of south Pembrokeshire: fossil karstic phenomena?' *Trans Instit Brit Geogr* **54**, 89–100

Walsh, P., Batteau-Queney, Y., Howells, S., Ollier, C. and Rowberry, M. 2008 'The gash breccias of the Pembroke Peninsula, SW Wales'. *Geol Today* **24**, 137–45

Maps

British Geological Survey 1:50,00 Sheet 244/245 Pembroke & Linney Head

Ordnance Survey 1:50,000 Sheet 158 Tenby & Pembroke

Ordnance Survey 1:25,000 Sheet OL36 South Pembrokeshire

The Andes Mountains and Magallanes Foreland Basin in southern Patagonia, South America

Bill Fitches[1] and Denis Bates[2]

[1] Bill Fitches, Geoscience Wales Ltd., Connaught House, Conwy, UK, LL32 8UB; billfitches83@hotmail.com
[2] Denis Bates, Institute of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, UK, SY23 3QQ; deb@aber.ac.uk

1. Introduction

Southern Patagonia is the part of South America that bends from its typical N–S Andean trend to E–W in Tierra del Fuego (Fig. 1). For overviews of the geology of this and neighbouring regions, papers by Biddle *et al.* (1986), by Wilson (1991) and by Galeazzi (1998) are recommended.

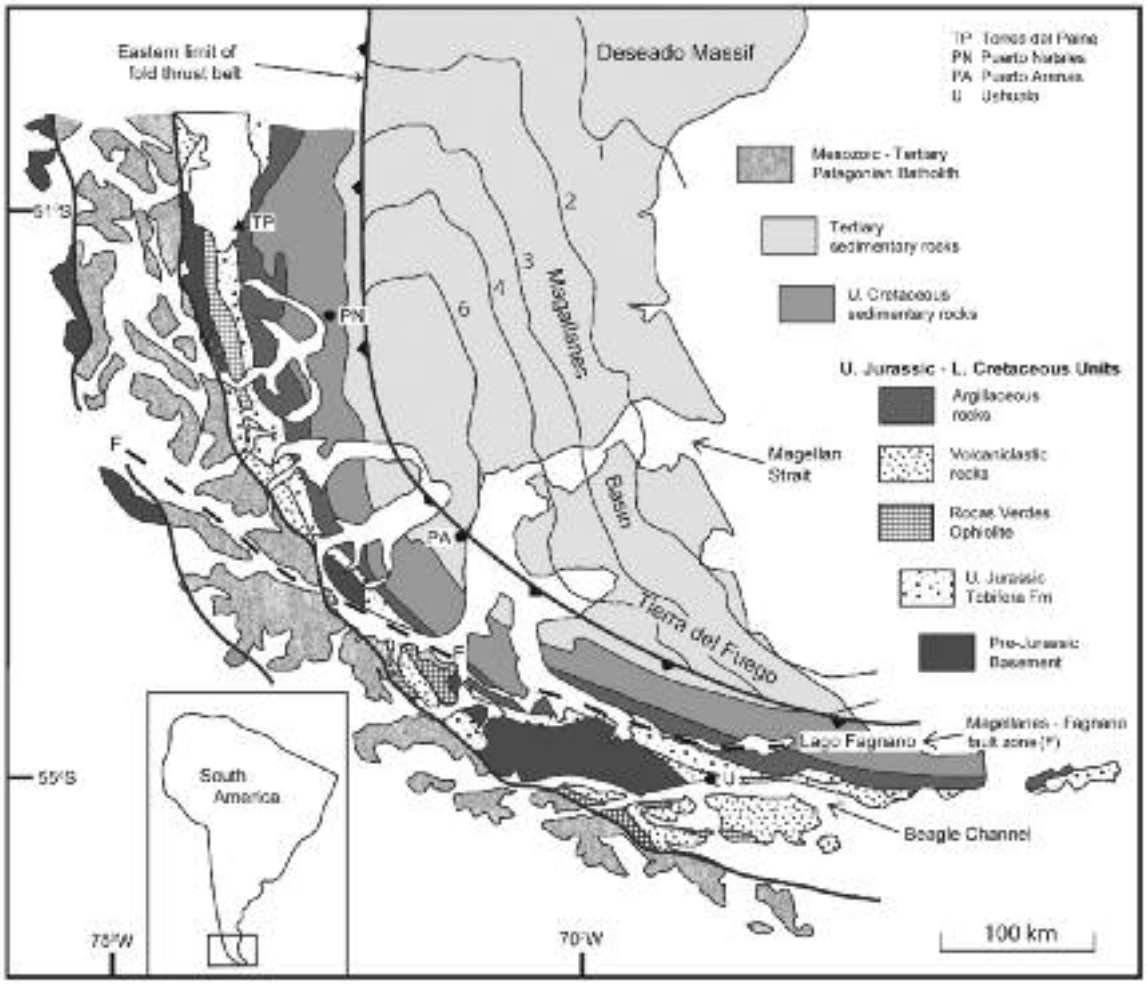
Much of the region once belonged to the Gondwana Supercontinent and was joined to what is now southern Africa. Southern Patagonia comprises Precambrian and Palaeozoic crystalline basement overlain by Mesozoic and younger assemblages. In the Jurassic, South America began to rift and drift from Africa. Shortly afterward, oceanic crust of the Pacific plates began to subduct the western flank of the continent, starting the growth of the Andean volcanic margin that continues today.

In front of the spectacular, high Andean mountains is the pampas, a low-lying plain that extends to the Atlantic coast. Below the pampas is an immense sedimentary trough, the Magallanes (or Austral) Basin, which is filled by Late Cretaceous–Tertiary sediments up to 7km thick. This trough is a foreland basin. It is asymmetrical, deepest in front of the Andes and wedging out northeastward. This shape, characteristic of foreland basins, is due to the eastward propagation of the Andean thrust front that loaded and depressed the western, axial parts of the basin floor. Near the Andean front the basin fill is folded and cut up by the forward-migrating thrusts, but most parts are virtually undeformed.

The Atlantic margin of the Magallanes Basin is an important source of commercial oil and gas. Black, oil-prone mudrocks are widespread in central parts of the basin. Hydrocarbons were generated from them during burial by the advancing Andean thrust sheets, which migrated up the gently inclined eastern flank of the basin and accumulated in reservoirs of porous sandstones.

One major visitor attraction of southern Patagonia is the rock spires of the southern Andes, which are carved from granite sheets, only emplaced *c*. 12Ma ago. Another attraction is the system of turquoise lakes along the Andean front, which occupy

Figure 1 Geological map of southern Patagonia, showing the Andes and the Magallanes Basin (redrawn and modified from Wilson 1991, fig. 1).



© OUGS ISSN 0143-9472

valleys cut by Quaternary glaciers descending from the Andean ice caps. These glaciers provide information about global climate changes.

The following account summarises the geological history of this region (Fig. 2), for the most part chronologically. It is based on a field excursion made to the region by BF, who is responsible for the text and photographs. DB compiled the maps and other graphics, basing them on figures given in acknowledged sources.

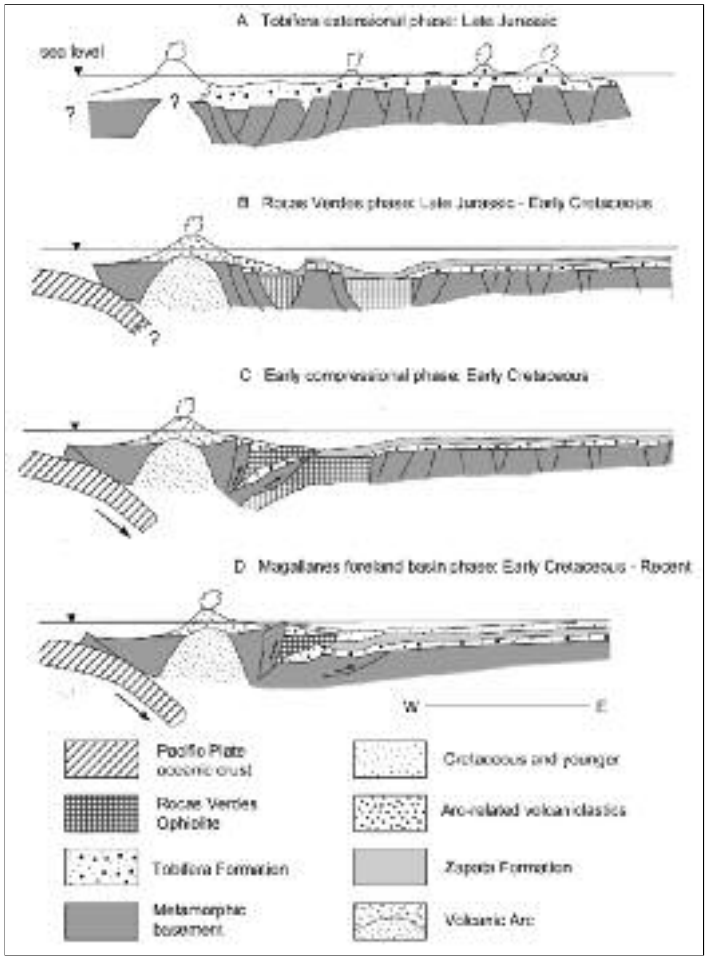


Figure 2 Jurassic to Recent evolution of the Andes and Magallanes Basin in southern Patagonia (redrawn and modified from Wilson 1991, fig. 15).

2. Pre-foreland basin stage: mid-Jurassic — early Cretaceous continental rifting and marginal basin development

2.1 Tobífera Formation and Rocas Verdes ophiolite assemblage

The volcanic rocks comprising the Tobífera Formation, of Middle to Late Jurassic age, covered one million or more square kilometres of Patagonia, and they represent the oldest, most extensive cover sequence in the region (Figs 1 and 2A). They are mainly rhyolite flows and pyroclastic deposits (Fig. 3), which rest with profound unconformity on crystalline rocks of the Gondwana basement. Only near the Andean Front are the volcanic rocks faulted and warped: elsewhere they are gently inclined towards the Andes. They were deposited in a network of active continental rifts, so their thickness is widely variable, up to 2,500m in places.

The continental volcanic rift setting has been attributed to hot-spot, mantle-plume activity associated with NE–SW extension that led to the break-up of this part of Gondwana and eventual opening of the South Atlantic. Westward, toward the Andes, the amounts of extension and crustal subsidence increased to give shallow marine conditions. Still farther westward, failure of the continental crust led to passive margin conditions and the formation of a small marine marginal basin floored by oceanic igneous rocks: the Rocas Verdes ophiolite assemblage of basaltic pillow lavas, sheeted dykes and ultrabasic rocks (Figs 1 and 2B).

Figure 3 Tobífera Agglomerate, Monte Fitz Roy region.

2.2 Zapata and Springhill formations

These formations of sedimentary rocks are broadly coeval, Late Jurassic to Early Cretaceous in age. The Zapata Formation is found in the west of southern Patagonia (Figs 1 and 2B), where it comprises mud-dominated turbidites that were deposited in deep water, perhaps at more than 1,000m depth. These sedimentary rocks overlie the Rocas Verdes ophiolite and adjacent passive margin sequence, and record the final stages of subsidence of that marginal basin before the onset of foreland basin development. The Springhill Formation, in contrast, is composed of coarse clastic deposits that represent continental and shallow marine settings marking a gently subsiding shelf situated well to the east of the marginal basin; it is not shown on our graphics. These deposits were derived in large part from the Tobífera volcanic rocks, and record the drowning of the continental rift environments. The Springhill Formation includes important hydrocarbon reservoirs.

3. Cretaceous–Tertiary Magallanes foreland basin subsidence

3.1 The axial zone

The onset of foreland basin subsidence is recorded in the axial zone by the sedimentary rocks of the Punta Barrosa Formation of early Late Cretaceous age, now exposed in the Andean foothills (Figs 1 and 2C, D). This formation, concordantly overlying the

Zapata Formation of the marginal basin stage, consists of sand-dominated turbidites (Fig. 4) that were deposited in deep water. The formation, up to 1,000m thick, wedges out eastward only a few kilometres from the axial zone and also thins out rapidly southward along the axis. This architecture is consistent with sediment derivation from the rising plutonic and volcanic rocks of the Andes and deposition in the infant foreland basin.

Subsidence of the basin axial zone continued into the Late Cretaceous as recorded by the *c.* 2,000m thick Cerro Toro Formation, which comprises mud-dominated turbidites brought in by currents flowing southward along the axis (Fig. 5). The axial zone in Chile at this stage appears to have been an extremely narrow trough, only 1,000m wide in the north and 4–8km in the south, but *c*. 100km long (e.g. Hubbard *et al.* 2008). Conspicuous among the mudstones are huge bodies of conglomerate and sandstone (Fig. 6, *overleaf, top*) elongated N–S, lenticular in cross section, which were deposited in channel complexes aligned along the floor of the basin axis. The coarse debris was carried in from a shelf to the north, itself composed of Andean detritus, and perhaps directly from the rising Andes by an oblique lateral channel. These channel complexes are being closely studied by researchers at Stanford University in the U.S.A., partly because they provide well-exposed and accessible analogues of deep-water, coarse clastic deposits that may have hydrocarbon reservoir potential in other parts of the world.

Figure 4 Punta Barrosa Turbidites, Monte Fitz Roy region. In the lower figure, the borehole (left of centre) diameter is c. *50mm.*

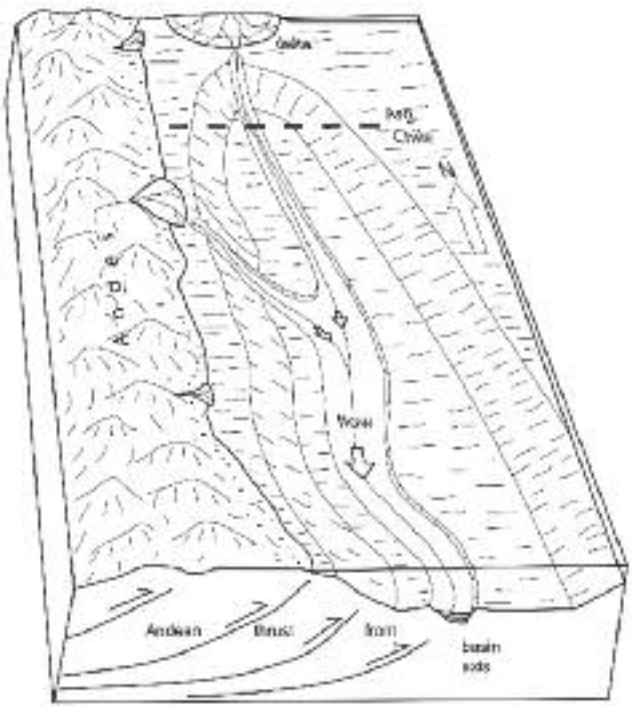


Figure 5. Flow of Cerro Toro turbidites along the N–S axis of the Magallanes Basin from a delta in the north, joined by a lateral channel from the Andes (redrawn and modified from Hubbard et al. *2008, fig. 15).*

A further 2,000m thickness of deep-water turbidites was deposited along the axis of the foreland basin in the latest Cretaceous, marked by the Tres Pasos Formation. This sequence wedges out westward against the Andes and eastward towards the shelf. The trough by now had widened to tens of kilometres. By the end of the Cretaceous some 7,000m of sediment had accumulated in the axial zone, and mostly in the *c*. 95Ma–65Ma Turonian–Maastrichtian interval: the sedimentation rate is therefore more than 200mm per 1,000 years, an extremely high rate, especially as much of this sediment was mud.

3.2 The Flank

North-eastward from the Andean front the floor of the Magallanes Basin gradually shelved towards the present-day Atlantic margin of Patagonia. In the Early Cretaceous, subsidence was an aftermath of the Andean marginal basin rifting, and the muddy deposits of the Lower Inoceramus Formation were broadly contemporaneous with deposition of the Zapata Formation to the west. The Middle to Late Cretaceous and Tertiary sedimentary rocks on the shelf, on the other hand, record subsidence associated with the development of the foreland basin, thinning and wedging out onto the shelf in the east, but thickening to the west and passing laterally into those of the trough. They include the Middle and Upper Inoceramus formations, named for the presence of the bivalve *Inoceramus*. Most of them are mud-dominated turbidites that were deposited on the shelf-slope and basin-plain. Up slope they passed into shallower water settings, where local carbonate mounds were formed, and where glauconitic sands (e.g. Zona Glauconitica Formation) and shaly limestones were deposited among the still predominantly muddy sediments. Conditions on the slope were widely anoxic, favouring the deposition of organic-rich mudrocks that provide important hydrocarbon source rocks.

Figure 6 Cerro Toro Conglomerate, Torres del Paine region. The upper plate shows light coloured resistant bed of conglomerate warped by an open syncline.

4. Foreland basin structure

The Mesozoic and Tertiary strata in most parts of southern Patagonia are nearly horizontal or gently inclined towards the Andes, being situated in the eastern limb of the foreland basin. Within a few tens of kilometres of the Andes, however, they have been folded and thrust faulted by the compression induced by the eastward advance of the Andean front into the axial region of the foreland basin (e.g. Diraison *et al.* 2000). The deformation is mild, for the most part, and took place under very low grades of burial metamorphism. Amounts of shortening in the fold-thrust belt are estimated to be in the range of 30km to 160km. The deformation began in the Middle Cretaceous as the foreland basin began subsiding rapidly, continued into the Late Tertiary and is probably ongoing.

Folds (Fig. 7) have wavelengths of several hundred metres, are upright to eastward verging and comprise open to close anticlines separated by flat belts and gentle synclines. These structures are commonly angular, a chevron style typical of folds produced at shallow crustal levels in thinly bedded, well-stratified rocks. The strata become cleaved within a few kilometres of the Andean Front.

The thrust faults are best seen on some seismic sections, mostly inclined towards the Andes and carrying hanging wall anticlines, separating duplexes and showing other examples of small-scale fold-fault relationships common in thrust zones. Some thrusts may steepen down-dip, nucleating on and rejuvenating steep normal faults that were active during the early Mesozoic extension. Such thrusts can be regarded as thick-skinned structures, as they involve deep crustal levels, although thin-skinned deformation predominated, affecting only the shallow crust.

As in many foreland basins, such as the Molasse Basin in front of the Alps and the Variscan Front of South Wales, drawing a precise limit to the deformation is not possible. The folds, cleavage and compressional faults each die out at different distances away from the Andes, and thrust faults probably continue farther basinward without being detectable because they follow bedding before becoming blind.

5. Oil and gas

Oil and gas are being extracted from wells along the Atlantic margin of southern Patagonia (e.g. Pucci 2006). The hydrocarbon source rocks are likely to be mostly mudstone turbidites that were deposited under anoxic conditions on deeper parts of the gently inclined flank of the Magallanes Basin. Some of the lacustrine shales in Tobífera rifts and shales among the Springhill fluvial deltaic deposits are also organic-rich, but their contributions to petroleum systems are probably low. Oil has been generated in a narrow, basin-parallel belt on the inclined flank at depths of 2–3km, and gas has been produced at deeper levels over a broad area to the west and south. The hydrocarbons have migrated 50–200km eastward and northward up the dip of the strata in the basin flank, reaching shallow reservoirs in a belt near the Atlantic margin. Among the best reservoir rocks are the shallow marine and fluvial deltaic sandstones of the Late Jurassic–Early Cretaceous Springhill Formation as well as shoreface sandstones of the Late Cretaceous–Early Tertiary Lower Magallanes Formation. The hydrocarbon reservoirs are sealed mainly by low-permeability shales and glauconite-rich sandstones, and most traps are stratigraphic and/or structures against normal faults.

Figure 7 Folded Cretaceous turbidites, Andean Front, Monte Fitz Roy region.

Figure 8 Lago Fagnano, along Magallanes-Fagnano fault zone.

6. The Patagonian orocline

A conspicuous feature of the tip of South America is the abrupt bend of major tectonic and topographical features, notably of the Andes themselves and the Magallanes Basin, from N–S in Patagonia to E–W in Tierra del Fuego. This right-angled arcuation was described as the South American Orocline by Carey (1958), who considered it to be due to rotation of an originally straight linear belt by later geotectonic processes. His interpretation was widely accepted, and the bending was explained by Tertiary plate movements in the Scotia Sea region that interrupted the original N–S continuity between the southern Andes and the Antarctic Peninsula.

The oroclinal bending interpretation was supported to some extent by palaeomagnetism studies (e.g. Burns *et al.* 1980), which pointed to rotation during the early Tertiary. However, the amount of rotation detected is much less than the 90° required to cause the entire arcuation. A comprise explanation is that part of the arcuation was indeed caused by rotation, but that most of the curvature was caused by the bending of structures around an original bulge in the margin of the South American plate during the collision with the Pacific plates to the west.

More recently, Ghiglione and Cristallini (2007) have used sandbox experiments to mimic the Late Mesozoic and Tertiary structures in the region. They found that pivoting of crustal blocks about the central part of the arc, as required in the oroclinal-bending interpretation, fails to recreate the sequence and patterns of deformation seen in the region. Similarly, a single-stage of NE–SW compression at right angles to an original bulge in the margin of the South American plate also fails to recreate the actual structures and sequence of deformation. On the other hand, a two-stage compression model against a major promontory in the South American plate did accurately replicate the patterns of folds and thrusts. This model involved initial NNE–SSW compression, almost normal to the Fuegan limb of the Andes, then WNW–ESE compression, at a high angle to the Patagonian limb and nearly parallel with the Fuegan limb. This two-stage model is consistent with the switch in convergence direction of the Farallon-Nazca Pacific plate that took place at *c*. 27Ma. On this evidence, the arcuation of the Andes and the Magallanes Basin is a primary feature, stemming from a bulge in the South American plate, and not the result of bending and rotation.

7. The Magallanes-Fagnano strike-slip fault zone

Between the Magellanes and Beagle straits in Tierra del Fuego there is a conspicuous topographic depression that passes ESE–WNW from the Atlantic to Pacific margins of South America, a distance of several hundred kilometres. This depression was cut along the trace of the Magallanes-Fagnano Fault zone by glaciers and rivers, and is marked in places by a chain of lakes that include the 100km long Lago Fagnano (Figs l and 8). Readers familiar with Loch Ness and the Caledonian Canal of Scotland may recognise a close analogy! The fracture belt, some 5km wide or more, is sometimes taken as the boundary between the South American and Scotia plates. It is generally agreed that the fault is a sinistral strike-slip structure on the basis of small-scale fault and fold patterns, but the amount of movement and timing are uncertain (e.g. Lodolo *et al.* 2003). Historical movements, accompanied by minor earthquakes and rare major seismic events (magnitude 7.8 in 1949), caused sinistral displacements on a cm–m scale. Estimates of the total movement range from a few kilometres to a few tens of kilometres, but in view of the width and length of the belt it is more likely to have been on a one hundred kilometre scale. Displacement may have started in the Late Tertiary when the subduction direction of the Andean margin switched from SSW–NNE to nearly E–W at *c*. 27Ma.

8. The Patagonian laccoliths

Among the most spectacular mountains of Patagonia are the clusters of immense pinnacles that make up the Monte Fitz Roy-Cerro Toro and Torres del Paine massifs: shapes similar to the spire of Salisbury Cathedral but steeper and reaching some 3,000m in height. Monte Fitz Roy (Fig. 9, *overleaf, top*) was known as ‘the smoking mountain’, but several others also had that name, so this one, the highest peak in southern Patagonia, was renamed after the captain of *The Beagle*. The Torres del Paine

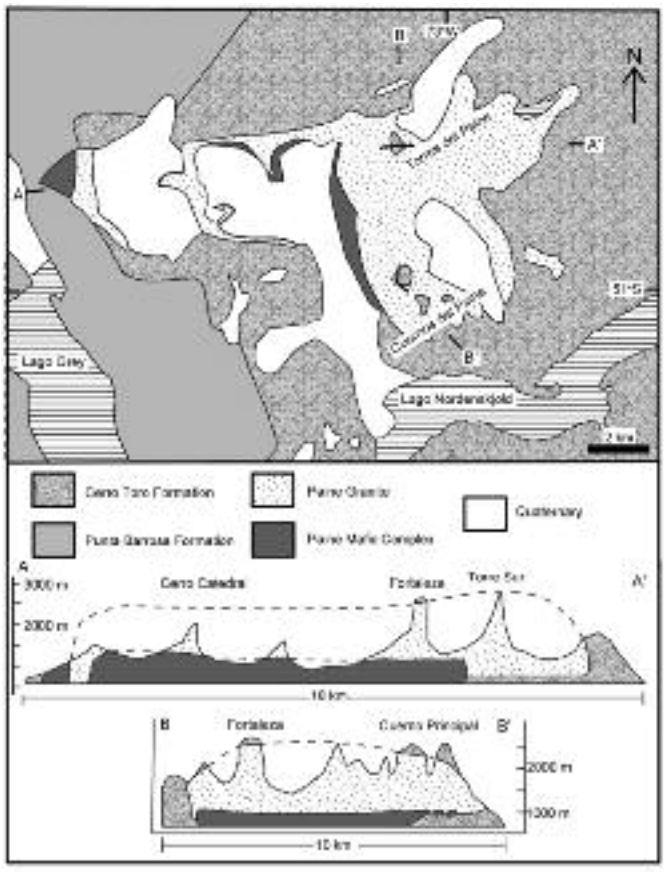


Figure 9 Miocene laccolith of Torres del Paine Intrusive Complex emplaced into Late Cretaceous sedimentary rocks of the Andean foothills (redrawn and modified from Michel et al. *2008, figs 1 and 2).*

are often known to climbers as the 'Towers of Pain'.* These two massifs (Fig. 1) are parts of an 800km long chain of six widely spaced, northward-younging Tertiary intrusions along a lineament that trends almost parallel with the Andes. They were emplaced mainly as laccoliths of granite into the sedimentary rocks of the Punta Barrosa and Cerro Toro formations of Cretaceous age (above), which had previously been folded and cut by thrusts. One interpretation is that these magmas, with alkaline compositions, were produced at sites of extension in the Pacific crust, which was being subducted obliquely beneath the South American continental plate.

The Torres del Paine intrusive complex (Figs 10, *below*, 11 and 12, *opposite*) has been studied in particular detail (e.g. Michel *et al.* 2008). Basal parts of the nearly horizontal, more than 2,000m thick laccolith are composed of basic and intermediate plutonic rocks. The main part comprises granite that reaches 2,000m in thickness and is best exposed, but largely inaccessible in the towers. The granite was emplaced as three sheets, successively younger ones penetrating along the base of the next older. The sheets have been dated as *c.* 12.5Ma (Miocene) using zircon U/Pb analysis, and so precisely that the age difference between the oldest and youngest sheet is defined as only *c*. 90,000 years. They were emplaced at depths of only *c*. 4km according to studies of the metamorphic mineral assemblages in the thermal aureoles. As unroofing and present-day exposure at altitudes of almost 3km has taken only 12Ma, average uplift rates were of the order of 500m per million years — some 50mm per century.

** See also (centre pages) Cuernos del Paine, Parque Nacional Torres del Paine, Cordillera del Paine, southern Chilean Patagonia; photograph © Bob Morley, one of our Moyra Eldridge Photographic Competition winners for 2010 — Editor.*

Figure 10 Monte Fitz Roy (centre) and Poincelot peak (left), Miocene granite(© Bill Fitches).

Figure 11 Cuernos del Paine: Cretaceous Cerro Toro turbidites (dark) intruded by light-coloured Miocene granite laccolith, Torres del Paine region (© Bill Fitches).

9. The Ice Age

The Patagonian Andes were heavily glaciated during the Pleistocene and still carry major ice fields that globally are among the biggest after those of the polar regions (e.g. Masiokas *et al.* 2009). From the ice fields numerous valley glaciers flow westward to the Pacific Ocean and eastward across Patagonia towards the Atlantic Ocean (Fig. 13, *overleaf, top*). Several of the eastern glaciers were huge; for example, the one that carved out the Beagle Channel was *c*. 250km long and several kilometres wide, and some reached the Atlantic margin. Since the last ice-age maximum, the eastern glaciers have receded great distances and the valleys they cut are commonly occupied by chains of lakes. Major lateral moraines, many tens of kilometres long, mark the positions of glacier margins and in places, as near Ushuaia (Fig. 14, *overleaf, bottom*), are exploited as construction materials. Much of Patagonia is smothered by immense, flat gravel plains left by the glaciers and their melt-waters, their monotony broken only by scatterings of small lakes occupying kettle holes and by low ridges marking former eskers and kames. Darwin (1860, 183–4) described the gravels and gave an early geotec-tonic interpretation of them.

Figure 12 Xenolithic granite of Miocene laccolith, Torres del Paine region.

Several of the major glaciers of the Andean foothills in Chile and Argentina are easily accessible tourist attractions, and the snouts of some can be approached from land and lake. The commonly visited Perito Merino Glacier (Fig. 13) can usually be relied upon to calve many times a day, giving rise to the myth that it is receding fast due to global warming; in fact, it is known to advance and retreat several hundred metres every few years. Many other glaciers in the region have receded since the last ice-age maximum, their irregular rates of retreat and minor advance under the control of many variables, such as precipitation rate, ice volumes, steepness and climate fluctuations.

Key references

Biddle, K. T. *et al.* 1986 'The stratigraphic and structural evolution of the central and eastern Magallanes Basin, southern South America', *in* Allen, P. A. and Holmwood, P. (eds) *Foreland Basins*. Internat Assoc Sedimentologists Special Publ **8**, 41–61

Burns, K. L., Rickard, M. J., Belbin, L. and Chamalaun, F. 1980 'Further palaeomagnetic confirmation of the Magallanes orocline'. *Tectonophysics* **63**, 75–90

Carey, S. W. 1958 'The tectonic approach to continental drift', *in* Carey, S. W. (ed.) *Continental Drift Symposium*. University of Tasmania, 177–355

Darwin, C. 1860 *The Voyage of the Beagle* (2 edn). Reading: Vintage (2009)

Diraison, M. *et al*. 2000 'Cenozoic crustal thickening, wrenching and rifting in the foothills of the southernmost Andes'. *Tectonophysics* **316**, 91–119

Galeazzi, J. S. 1998 'Structural and stratigraphic evolution of the western Malvinas Basin, Argentina'. *Amer Assoc Petrol Geol Bull* **82**, 596–636

Ghiglione, M. and Cristallini, E. 2007 'Have the southernmost Andes curved since Late Cretaceous time? An analog test for the Patagonian orocline'. *Geol* **35**, 13–16

Hubbard, S. M., Romans, B. W. and Graham, S. A. 2008 'Deep-water foreland basin deposits of the Cerro Toro Formation, Magallanes basin, Chile: architectural elements of a sinuous basin axial channel belt'. *Sedimentol* **55**, 1333–59

Lodolo, E. *et al.* 2003 'Magallanes-Fagnano continental transform fault (Tierra del Fuego, southernmost South America)'. *Tectonics* **22**, 1–25

Masiokas, M. H. *et al.* 2009 'Little Ice Age fluctuations of small glaciers in the Monte Fitz Roy and Lago del Desierto areas, south Patagonian Andes, Argentina'. *Palaeogeogr, Palaeoclimatol, Palaeoecol* **281**, 351–62

Michel, J. *et al.* 2008 'Incremental growth of the Patagonian Torres del Paine laccolith over 90 ky'. *Geol* **36**, 459–62

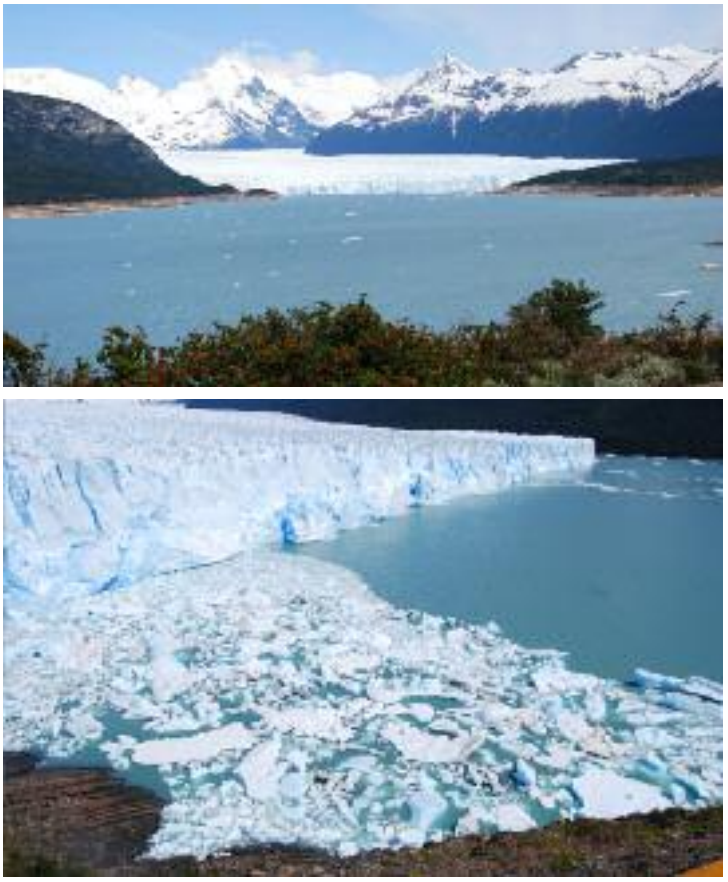


Figure 13 Perito Merino Glacier, Lago Argentino area, between the Torres del Paine and Monte Fitz Roy regions.

Pucci, J. C. 2006 'Southern offshore basins of Argentina underexplored'. *Oil Gas J* [2006], 30–3

Wilson, T. J. 1991 'Transition from back-arc to foreland basin development in the southernmost Andes: stratigraphic record from the Ultima Esperanza District, Chile'. *Geol Soc Amer Bull* **103**, 98–111

Figure 14 Marginal moraine (light-coloured) along the northern flank of Beagle Channel, near Ushuaia.

Book review

Strachan, Rob, Alsop, Ian, Friend, Clark and Miller, Suzanne 2010 *An Excursion Guide to the Moine Geology of the Northern Highlands of Scotland*. National Museums Scotland (ISBN 978-1-90526-733-0; paperback, 298 pages; £17.99)

This is a beautifully produced and handily sized (A5) paperback book, which will fit in a backpack. At 648g weight I would not take it up a Munro, but for car-trips it is ideal. It has clear print, many maps and diagrams, a helpful contents page and a list of references at the end.

There are 14 excursions of varying lengths and requiring different amounts of physical effort covering the whole of North West Scotland beyond the Great Glen Fault. It incorporates some Devonian and younger rocks as well as the Moine. The book starts with a chapter summarising the regional geology, which I found very interesting and updated my somewhat outdated knowledge of the area. Each excursion is colour-coded so that it can be easily identified in the book. There is a box giving basic information: maps required, terrain, length, weather warnings, SSSIs, stalking and midges. If more than a day is needed, it says so. Similarly the locations for a shortened version are also given. Some excursions also include diagrams, photos and tables as well as maps.

As I had just returned from walking in Glen Shiel, I used Excursion 5 as a 'test'. The instructions seem fairly straightforward, with clear explanations. It is very much up to the reader/leader to find the structures but should not be beyond an amateur. Non-professionals might need a geological dictionary on first reading, for some technical terms, as there is no glossary. The maps appear very helpful. I was pleased to find that I had correctly identified the types of rocks and structures that I had seen. My criticisms would be that some of the colour differentiation could be better — there is light purple and a slightly darker light purple — not easy to differentiate between in poor light. I would also have expected that the option of starting from Kyle of Lochalsh would have been considered.

Overall this looks a very useful book and I will be purchasing my own copy, as I visit the area at least once a year — it is much easier reading that the BGS memoirs!

— Jane Michael, BSc (Hons) Open (Natural Sciences with Earth Sciences)

Book review

Emeleus, C. H. and Troll, V. R. 2008 *A Geological Excursion Guide To Rum: The Palaeocene Igneous Rocks of the Isle of Rum, Inner Hebrides*. Edinburgh Geological Society in association with National Museums Scotland (ISBN 978-1-90526-722-4; paperback, 150pp; £12.99)

The island of Rum, situated off the north west coast of Scotland, is formed by a ridge of Archaean Lewisian gneisses and Late-Proterozoic Torridonian sandstones. About 60Ma these rocks were intruded by magmas to form the Rum Central Igneous Complex. After an initial phase of silicic magmatism and ring faulting, more basic magmatism led to the development of extensive bodies of basic and ultrabasic plutonic rocks with repeated modal layering. Within the layered rocks there are distinctive crystal textures that are used to interpret what was going on within the magma chamber at the time of emplacement. Subsequent subaerial erosion has exposed the heart of this volcanic complex and it is these plutonic rocks that form the real attraction of Rum for geologists.

This Rum guide concentrates on these igneous rocks and has been written by two of the leading experts in this field. The introduction consists of information essential to anyone planning to get to the island and stay there to do fieldwork. Based on my own experience there last summer, these details are accurate and helpful.

The next 23 pages comprise a brief summary of the geology of the island, with most space given to the igneous rocks. This is where the character of the book becomes apparent. While the narrative is clearly written for anyone familiar with igneous geology, it is not aimed at the casual traveller. Geological terms are introduced without explanation on the understanding that the reader will be fully conversant with them. For the trained geologist, however, this makes the essential information available in a compact volume that can be carried in a coat map-pocket.

The largest part of the book, 110 pages, consists of the descriptions of nine excursions to visit selected exposures around the island. Some of these excursions are quite long and, given the mountainous nature of the terrain, might be a bit too arduous for some. However, the guide includes with each route an indication of its length, and suggestions for short cuts or safe descents from the mountains.

Every exposure is identified on a coloured map and has its own eight-figure Ordnance Survey grid reference and a description of what is to be seen there. During my own visit to the island this enabled me to assemble my own selection of routes to visit those exposures that had a particular interest to me. In a week of fieldwork I only failed to find one exposure, but as that was on a morning of torrential rain and strong wind it is quite possible that the error was mine.

The guide is about A5 in format (not dissimilar to an Ordnance Survey Landranger map) and printed on heavyweight glossy paper with a water-resistant coating. It is, therefore, well suited for use in the field. It is generously illustrated with helpful colour photographs and maps, although, as the guide makes clear, the latter are not really adequate for navigation across the island. I used the Ordnance Survey Explorer map number 397 (1:25 000 scale), with compass and GPS for navigation to get around, as there are no roads on the island and only a few recognised tracks.

This book is finished to a very high standard and seems to be remarkable value for its £12.99 cover price. My own copy coped easily with the rigours of a week of intense fieldwork. Rum is a spectacular place for igneous geologists and this guide will help the visitor get to see the best that the island has to offer.

— Peter Wood, BSc (Hons), ARSM, FGS

Book review

Wyse Jackson, Patrick N. 2010 *Introducing Palaeontology: A Guide to Ancient Life*. Dunedin (ISBN 978-1-90671-615-8; paperback, 152pp; £9.99)

The author's target readership is members of the general public who have an interest in fossils, and first and second-year students in geology, biology and palaeontology.

The text is in two columns making the book wide for its height; and there are 102 interspersed figures, many of which have multiple images. Chapter numbers, headings and sub-headings are picked out in vivid blue and red. New technical terms are in bold type and the reader is referred to a glossary at the end of the book for these terms' meanings. There are 490 terms in the glossary, an average of 3.5 per page. One page alone has 24 highlighted terms. The illustrations, attributed to John Murray, are beautiful. Background colours are used to present exhibits as works of art. Diagrams of the workings of organisms are exceptionally clear. The book is easy to handle and seems small and robust enough to take into the field.

Part 1 discusses fossilisation processes, fossil collection (emphasising good practice), and methods of study and display. Chapters cover taxonomy and the role of fossils in interpreting the history of life on Earth, evolutions and extinctions, environments, climate and timescale. Locations of important fossil assemblages are introduced and their significance explained. Part 2 has 18 chapters on fossil groups, ranging from algae to trace fossils.

The author is a museum curator, a historian of geology and a bryozoan expert. These attributes influence the book's strengths. The history of geology is used to make names of geological periods interesting; the story of how and why 19th-century fish fossils were parted and later reunited is heartwarming. The book ends with a sad account of Rev. William Buckland's mental deterioration. One is left wondering if this was due to taking taxonomy one step too far!

The lay reader will enjoy the illustrations, aspects of fossil collection and historical aide-memoires. The need to consult the glossary so often may be discouraging. Weeks rather than days will be needed to do the book justice.

This reviewer is in the group of intended undergraduate readers. I learned that the Carboniferous is now the Mississippian and Pennsylvanian; and as a result of reading the book I have become especially interested in bryozoans, graptolites and conodonts. The author's relaxed approach to phyla and class made sense and there was a sceptical undertone to the discussion of birds and hominids.

My conclusion is that the book is a visual feast and a lot of hard work for the lay reader; and an inexpensive stimulation for the undergraduate.

— Bill Hinton, OU student

Book review

Forey, Peter L., Cavin, Lionel, Longbottom, Alison and Richter, Martha 2008 *Fishes and the Break-up of Pangaea*. London: Geological Society (ISBN-10: 1-8623-9248-X, ISBN-13: 978-1-86239-248-9; hardback, 376 pages; £95)

I picked this book out of the review box last year because of its interesting title. This was a field of which I had little knowledge, but it sounded very intriguing. I rapidly found myself quite out of my depth in the primordial ocean.

There were words that I did not know and that were not in any of my dictionaries. I knew, roughly, what 'radiation' meant, but had never heard the term 'vicariance'*. (While reading the book, I was away with a group of OUGS members, so I asked some of them, but nobody knew the term. So I had to enquire further.)

The book is a collection of papers put together by his colleagues to honour Dr Peter L. Forey, "in recognition of his great contribution to fish systemics and palaeobiography". Dr Forey recently retired from the Natural History Museum, London and I discovered is the leading authority on coelacanth phylogeny and a mover in the 1980s in the, then, new science of cladistics.**

The papers start with studies of Triassic chondrichthyans and lungfishes and an examination of Triassic palaeogeography. The distribution and phylogeny of Late Jurassic neoselachians and teleosts are considered and followed by five papers on Cretaceous fishes, their distribution and evolution. Finally six papers deal with Tertiary fishes, eels, ceolacanths, bony tongues and others.

Parallels are drawn between the fish phylogenies and the palaeolgeographic models.

The paper on Cretaceous bony fishes has a series of particularly helpful cartoons of continental breakup set alongside evolutionary trees, which enable the non-specialist to differentiate between radiation, vicariance and dispersal events.

All the papers are really aimed at the specialist palaeontologist or at the serious student of fish evolution, but all are fascinating.

On 'Googling' the title I discover that much of the text can be found on the net at:

books.google.co.uk/books?isbn=186239248X

so you can explore this fascinating book for free, or borrow it from the OUGS library.

— Mary Howie, BA (Hons) Open (Maths, Physics and Geology)

* vicariance: the splitting of a range of a taxon; vicariance biogeography studies the relationships between biogeography and continental drift

** From the net (books.google.co.uk/books?isbn=186239248X): Dr Peter L. Forey is a researcher into fossil fishes at The Natural History Museum, London. His overall research interests concern cladistic analysis of combined fossil and Recent morphological data in various groups of fishes. Lately, he has focussed on three systematic areas: 1. Coelacanth phylogeny and the patterns of speciation and morphological evolutionary trends within the group; 2. phylogeny of lower teleostean fishes and their distributional and ecological history throughout the Cretaceous; 3. the relationships of conodonts. Along side this empirical work, he is also interested in more theoretical aspects of missing data in cladistic analysis, methods of coding data and the theoretical and practical aspects of combining all data to a primary matrix.

Columnar jointing: a review of recent research

Michael Perkins (perkinsmg@gmail.com)

Abstract

Columnar jointing is commonly developed in thick lava flows, with good examples in the British Isles and around the world. In recent years, research has provided new insights into the mechanisms of its formation and what the columns can tell us about cooling history. The current thinking is reviewed, taking in field evidence, experimental work and numerical modelling.

Introduction

Fingal's Cave on Staffa and the Giant's Causeway in Northern Ireland are two world-class localities in which to see columnar jointing in basalt lava flows. However, the phenomenon of columnar jointing is widespread throughout the world and is developed to a greater or lesser degree in many thick lava flows, with particularly fine examples at the Devils Postpile in California, the Devils Tower in Wyoming, and in Iceland (Fig. 1). Columns are even known to exist on the moon and Mars (Milazzo *et al.* 2009).

Figure 1 Basaltic columns in lava flow of Late Tertiary age, Snaefells Peninsula, Iceland (© M. Perkins).

Over the years much research has targeted understanding the mechanisms controlling columnar joint formation in order to address a number of questions. These include what physical processes cause formation of the polygonal columns, the characteristics of the materials in which they develop, and the controls on column size and shape distribution. This article aims to shed some light on how thinking on these issues has progressed.

Anatomy of a columnar lava flow

Fingal's Cave on Staffa (Fig. 2) is a good example of the presence of well-formed basalt columns up to a certain height (known as the *colonnade*), with an abrupt change to a chaotically ordered or curvi-columnar layer above (the *entablature*). Some flows also show an upper colonnade, above the entablature, often with narrower columns. These terms were first used by Tomkeieff (1940).

Figure 2 Fingal's Cave, Staffa, Scotland. The colonnade and overlying entablature can be clearly seen (© M. Perkins).

Occasionally, pillow-like features are found beneath the bottom tier of columns. These are known collectively as the *pillow palagonite complex* and are thought to form if the lava flow encounters standing water (Milazzo *et al.* 2009).

Host rocks and mechanism of formation

The host lithology both at Staffa and at the Giant's Causeway is a flood basalt of Tertiary age. Columnar jointing can also be seen in many exposures of extrusive and intrusive Carboniferous basaltic rocks in the Midland Valley of Scotland (Fig. 3). Although associated most with mafic lavas, columnar jointing is also found in andesites and rhyolites, and can even form in sandstones (Fig. 4, *overleaf*) as they cool

Figure 3 Gently dipping wavy columns in the Dunglass volcanic plug, near Glasgow (© M. Perkins).

© OUGS ISSN 0143-9472

Figure 4 Columnar joints in sandstone, Bute, Scotland (photo: A. Burgess http://www.geograph.org.uk/photo/4827).

after being heated by plutonic intrusions (Blackstone 1963). The phenomenon is also not limited to petrology.

As a solidifying lava cools, thermal contraction causes stresses to increase within the rock until fracture occurs. Joints then propagate from a crystallised exterior towards a warmer interior, trailing slightly behind the solidus (Goehring *et al.* 2006). The fracture front propagates through the flow starting from, and parallel to, a cooling surface, with the fractures themselves orientated perpendicular to it. In lavas this surface tends to be horizontal and leads to vertical columns, but horizontal or other column orientations may develop in intrusive bodies.

This crude description is fairly well accepted. However, fracturing in thin layers of material shows cracking with primarily 90˚ angles between the faces, rather than the predominantly 120˚ angles of well-formed basalt columns. This has led to the proposal of two models to explain the regular pattern observed in lavas.

Thermal contraction

It is well understood that a hexagonal pattern in two dimensions permits the maximal release of stress per unit fracture length, and thus minimises the energy of the system (Mallet 1875). The thermal contraction model suggests that, despite the formation of an unordered cracking pattern on the top surface, as a lava cools and the cracks propagate into the flow the pattern will evolve towards its preferred, low-energy honeycomb form. However, even a mature pattern will not necessarily achieve this perfect symmetry, and some disorder will remain in the system (Goehring and Morris 2005; Jagla and Rojo 2002).

Constitutional supercooling

Some researchers, however, believe that an isotropic stress field cannot in itself lead to the observed polygonal patterns. As homogeneous materials do not seem to develop hexagonal joints, a mechanism known as 'constitutional supercooling' has been invoked to try to explain a regular pattern of weaknesses in an inhomogeneous material such as a lava. As it crystallises, a lava will tend to leave behind a melt of more felsic (Gilman 2009), or volatile-rich (Guy 2010) composition, and this lower melting-point material cannot quickly diffuse away from the solidification front. This leads to instabilities causing the development of *fingering*, where the solidification begins at regular intervals on the isothermal surface, leaving more evolved regions between them. On final solidification this forms regions of low strength arranged in an approximately hexagonal pattern, which are more susceptible to brittle failure.

Field evidence lends some support to this hypothesis. Guy (2010) points to various circular and radial patterns, such as bubble circles and radiating textures, seen in cross-sections through columns that are difficult to explain using the thermal contraction model or indeed subsequent meteoric weathering (Fig. 5). Moreover, on occasions, jointing forms without the joints themselves opening, which is not suggestive of thermal contraction alone.

Difficulties for the fingering mechanism arise from the fact that consistent compositional changes have not been detected across a slice of column. In addition, the process does not seem appropriate to all materials in which columnar jointing occurs (Müller 1998b). Guy himself also recognises that thermal contraction does have a role to play, particularly in the formation of regions where columnar jointing is more chaotic in nature.

Controls on column formation

In nature, columns form with a wide variety of scales, usually of the order of tens of centimetres but with columns recorded from one millimetre up to four metres in diameter. Some of the tallest are found at Devil's Tower, Wyoming, where spectacular columnar jointing is developed in a trachytic lava flow to a height of a thousand feet. Basalt columns can also cover enormous areas — for example columns of the Columbia River Group are believed to cover central Washington State, extending into Oregon and Idaho. What controls these variations in scale?

Experimental work

Many insights into columnar joint formation have come from experimental work. Cooling lavas can be somewhat impractical to handle, although some observations have been made on a Hawaiian lava lake (Hardee 1980). More conveniently, an early observation (Huxley 1881; French 1922) was that a slurry made of cornstarch and water contracts as it dries, with desiccation leading to the formation of polygonal columns. This fact remained forgotten for many years, until rediscovered independently by Müller (1998a; 1998b). Experiments on drying cornstarch under controlled conditions (using a lamp situated above the starch to control drying speed) have since shed new light on the factors affecting column formation. Indeed, the basic experiment is sufficiently simple that it can be done in the home (Goehring, http://www.lgoehring.com/Starch_columns.html).

Starch studies are useful, as they provide a close analogue for processes occurring in cooling lavas. Müller (1998b) shows that diffusive processes operate in both materials and obey the same physical laws, with temperature in lavas being equivalent to water concentration in a starch slurry. However, the differing sizes of the diffusivities in the two materials means that starch columns form on a much smaller scale than basalt columns do.

We are accustomed to the fact that a slow cooling rate leads to larger crystal formation, so it is natural to surmise that the same might hold true for columns. According to Müller (1998a),

Figure 5 Large pentagonal column slab, Snaefells Peninsula, Iceland. Within the slab, a quasi-circular structure can be seen. Patterns like these have been used to support constitutional supercooling (© M. Perkins).

the primary control on column formation is the diffusivity of the material. This can be thermal diffusivity, as in lava flows, or hydraulic diffusivity, in the case of starch slurries. The size of the diffusivity in turn controls the temperature or water concentration gradient in the material. There is some disagreement on whether it is this gradient, rather than rate of cooling *per se*, that affects the size of the columns formed (Müller 1998b), with the two parameters differing by a factor of the speed of advancement of the cracking front. This subtlety aside, slower cooling generally gives rise to larger columns, with either column diameter (Grossenbacher and McDuffie 1995) or cross-sectional area (Toramaru and Matsumoto 2004) being inversely proportional to cooling rate. In the interior of the flow, the cracking front advance reaches a steady state, making the distinction between cooling rate and temperature gradient somewhat moot.

From analogue behaviour seen in starches, the latter researchers predict a critical lower cooling rate limit for which columns will form at all. As the limit is approached, column size appears to increase without bound. Similar behaviour seems to have been observed by Müller (1998b), who reported that some columns stopped propagating part of the way into the cake.

By regulating the starch drying speed using a computer feedback loop, Goehring *et al.* (2009) accurately controlled the speed of the advancement of the desiccation front, again confirming that faster drying speeds led to formation of smaller columns. Uncontrolled drying led to a size increase with depth, as the cracking front decreased in velocity as drying proceeded. The analogue in lavas that, as we suspected, a faster cooling rate is linked to smaller columns is also evidenced in the field by the correlation of crystal size in the intrusion with column diameter. Goehring *et al.* conclude that in very thin flows or very slow cooling rates, the columns either do not form at all or have column diameters of the same order as the flow thickness. Thicker flows have columns sizes independent of the flow thickness except inasmuch as this affects the cooling rate.

The same group also conducted experiments varying the initial or final drying rates. The result was that, all else being equal, column size appeared to be more dependent on the initial drying rate, which seeds the initial crack pattern, than on later conditions (Goehring *et al.* 2006). Thus it appears that the column size depends strongly on cooling history (hysteresis) rather than on the cooling rate at a particular point in time. Cracks might migrate and merge, but do not tend to nucleate in the interior of the flow, and a number of column scales can be stable for a given cooling rate. In addition, while drying of the starch slurries proceeds from the top, the columns do not start right from the top surface. Instead, a chaotic pattern formed at the surface only becomes gradually organised into regular columns with depth.

Figure 6 Columnar jointing developed in cornstarch. Polygonal columns of differing numbers of sides, mega-joints and striae on the column faces, can all be seen (photo from Müller 1998a).

Figure 7 'Brick wall' like texture showing 'chisel marks' or striae, on face of basaltic column, Snaefells Peninsula, Iceland (© M. Perkins).

Mega-joints

Additional parallels are seen between basalt and starch columns (Fig. 6). First, large mega-joints or master joints form through the flow prior to column formation. This first-order pattern forms a sparse pattern of wide cracks across the surface. Intersections between these cracks tend to be at 90˚, with the cracks penetrating to the bottom of the starch cake. Subsequent, second-order polygonal columns form later, and the additional drying surface caused by the mega-joints may cause the columns to curve in their vicinity (Lodge and Lescinsky 2009). This phenomenon has also been observed in lavas (Lyle 2000).

Striae

In starch cakes, horizontal striae are often seen on the faces of the columns (Fig. 6). In lavas, these striae, or 'chisel marks', may form a 'brick wall'-like texture (Fig. 7). These reflect the periodic growth of the fractures, and their height has been postulated to be inversely proportional to temperature gradient (albeit with a small fracture length dependence), as they are believed to propagate across a constant temperature change (Grossen-bacher and McDuffie 1995). Tension in the lava increases until it exceeds some threshold. At this point the rock fractures, and the crack propagates into the warmer interior, which is subject to less stress. Smooth portions of the striae occur where the rock behaved in a brittle fashion, terminating in a rougher texture formed in the warmer, more ductile interior where crack advance was temporarily arrested. This, along with plumose structures on the striae can be used to show the direction of crack advance. In colonnades beneath the entablature, cracking proceeds from the *base* of the lava flow, while above the entablature it proceeds from the surface (Lyle 2000). Cornstarch experiments have as yet only permitted drying from the top surface.

Goehring and Morris (2008) gathered large quantities of field data from exposures of the Columbia River Basalt Group. Measurement of some 1,200 stria heights showed that, in general, stria heights are proportional to column diameters, although close to the cooling surface, stria height increases linearly with distance from it. In the interior of the flow, each crack advance behaves independently of previous ones, with no relationship between successive stria heights.

Wavy columns

A phenomenon as yet only observed in lavas is wavy columns (*see* Fig. 3). In these, the width of a column undulates along its length, with wavelength of the oscillations significantly greater than the stria height, and of the same scale as the column diameter (Goehring and Morris 2008). The mechanism of their formation is as yet unclear, but may reflect an oscillatory instability during the advancement of the fracture tips.

Formation of entablature

Various explanations are put forward for the existence of the entablature layers. One widespread assertion is that, in lavas, the entablature layer is formed by high cooling rates near the surface owing to infiltration of water into the lava. This may be due to high precipitation, or as a result of the displacement of rivers by the lava, which then flows over the top of the lava flow. Many field observations support this hypothesis, with evidence coming from palaeotopographical and palaeobotanical studies, the presence of fluvial sediments and hyaloclastite, and the quenching of the lavas. Flooding of the early-formed master joints (Lyle 2000) can lead to an entablature with narrow, fanning columns. Alternatively, periodic flooding events during the formation of a downward-cooling colonnade can cause entablature layers to form at multiple horizons within the flow. This explanation is used to support the former existence of surface water on Mars, where entablatures in multi-tiered flows have been detected (Milazzo *et al.* 2009).

However, the apparent existence of entablatures formed in desert environments causes problems for this theory. Guy (2010) instead puts the entablature layer down to the difference between layers where thermal contraction processes are important (rapid cooling) and those where constitutional supercooling comes into play. If supercooling occurs at all in the entablature, it takes on a more chaotic function there.

In starch experiments using a decreasing drying rate, Goehring and Morris (2005) noticed that a particular column size could be stable up until a critical depth, when the pattern would abruptly change to one with a much larger average size. This abrupt change would come about through a large number of column merges and fracture terminations, and would result in a fairly chaotic layer within the cake — somewhat akin to an entablature layer — resulting from the transition to a new stable column scale.

A final observation is that in real lavas cooling proceeds from multiple surfaces. Where the two upward-cooling and downward-cooling regions meet, distortion of the columns and changes in column scale can occur (Budkewitsch and Robin 1994), although often the regimes meet along a sharp, quasi-planar surface (Xu 1980).

Materials and mechanisms of heat loss

Columnar jointing does not seem to develop in all materials. This was cited as a possible justification for the constitutional supercooling hypothesis. However, an alternative explanation is that columnar jointing results from the relative influence of two means of cooling: the conduction that occurs through the columns themselves, and convection through the opening fractures between columns. In starches, drying also occurs through the fractures while capillary action advects moisture within the starch itself. It is the separation of these two regimes (and, by analogy, the conduction and convection regimes in basalts) that causes column formation (Goehring *et al.* 2009).

Budkewitsch and Robin (1994) imagine convection cells set up along the column faces, with heat transported by fluid flow. This requires the presence of a fluid when columns develop in intrusive bodies. Goehring and Morris (2008) believe that the narrowness of the cracks means that capillary action, rather than gravity, draws water through the convection cells. This means that the same mechanism can operate in both the downward-cooling and upward-cooling colonnades.

Which fluid phase is available for convection has an impact on cooling. While usually an upper colonnade consists of narrower columns than a lower one, on occasions the reverse is true. This may suggest the dehydration of underlying sediments provided water for the lower cooling process (Budkewitsch and Robin 1994).

Figure 8 A selection of Giant's Causeway polygons with varying numbers of sides (photo: M. Perkins).

Polygons

The expectation is for polygons in columnar jointing to be six-sided, giving rise to *pseudohexagonal* symmetry — that is, six-fold rotational symmetry that does not reflect an underlying hexagonal crystal system. As we noted, hexagonal columns are favoured to minimise the strain energy during cracking. However, in nature, pentagonal columns are often as common as hexagonal ones, even in mature patterns such as the Giant's Causeway (Fig. 8, *previous page*). In practice, columns with between three and eight sides are often found (Budkewitsch and Robin 1994), and the polygon side statistics are remarkably constant worldwide.

As distance from the cooling surface increases, it is often observed that the columns broaden and merge, and their number decreases (Goehring *et al.* 2006). As distance from the cooling surface increases, it is often observed that the columns broaden and merge (Goehring *et al.* 2006). Consequently the number of polygons decreases, giving a chance for the five- and seven-sided polygons to be weeded out in favour of six-sided ones as the pattern matures (Lodge and Lescinsky 2009). Cornstarch experiments (Fig. 9) seem to confirm that higher cooling rates lead to columns with fewer sides, pentagons being more common for higher drying rates and hexagons for lower rates (Toramaru and Matsumoto 2004).

Most of the experiments discussed above assumed a static pond of cooling lava, so that an isotropic stress field develops during contraction. In an effort to explain different styles of columnar jointing, experiments have been performed that subjected drying starch slurries to extensional or compressive stresses, by causing movement to one side of the container during drying (Lodge and Lescinsky 2009). These give a variety of different columnar patterns, ranging from the formation of curved columns, horizontal columns or brittle failure depending on the magnitude and sense of the stress. Near the moving boundary, the orientation of fractures showed preferred alignment parallel to the imposed stress, disrupting the formation of hexagonal columns. Farther from the boundary, the polygon shape statistics were normal. The group suggested that the results may have an analogue in the ponding of lava against a melting glacial wall.

Numerical models

Attempts have also been made to model columnar joint formation numerically. Quite simple models can demonstrate features seen in real lava flows.

One attempt (Budkewitsch and Robin 1994) started with a crack pattern splitting the surface of the flow into an arrangement of random Voroni polygons (Boots and Murdoch 1983) of different sizes and number of sides. The isotherms were computed and cracks were assumed to advance parallel to the highest thermal gradient. As larger polygons are warmer than smaller ones, this model will direct the crack propagation towards the larger polygons. Thus as the cracking front advances, the polygons tend to equalise in size and the number of sides tends towards six, so that the columns mature towards a regular, hexagonal arrangement.

An alternative investigation (Saliba and Jagla 2003) used a numerical method to compute the stress ahead of the cracking front. The pattern was seeded with an arrangement of octagons and squares, which simplified the stress field calculations. The model predicted the evolution of an initial pattern towards one

Figure 9 Section through columns formed by desiccation of cornstarch, showing a distribution of polygonal shapes (photo: L. Goehring).

in which equi-dimensional hexagons would dominate, and increase in size with depth, but also suggested a dependence on the scale of the initial pattern. A novel prediction of this model was that the columns would have slightly curved faces, concave into the larger polygons, which they hoped could be correlated with field evidence.

The fact that the curved faces helped to equalise polygon areas was consistent with earlier work by Jagla and Rojo (2002). Using a step-wise advancement of the cracking front and moving in the direction of decreasing energy, they iterated from a random surface crack pattern to one that closely resembled the Giant's Causeway polygon statistics at depth. The energy term used contained a term proportional to column cross-sectional area, at a minimum when polygon areas were equal.

Recent work has taken on the daunting problem of solving the stress field for an arbitrary crack shape in an infinite two-dimensional elastic medium (Bouchbinder *et al.* 2008). It will be interesting to see if further work in this direction can be used to permit a more realistic modelling of the initial development of polygons.

Conclusion

Columnar jointing is a common feature of cooling rocks, being particularly prevalent in basaltic lava flows. Despite the fact that it has aroused the curiosity of scientists for centuries, the mechanisms of its formation, and the precise controls on the sizes of the columns, are still a hot topic of research and debate.

While opinions still vary on exactly what causes the development of the polygonal pattern, consensus does seem to have been reached in two areas. First, columns form by advancement of the cracking front away from the cooling surface, with the regularity of the hexagonal pattern increasing with distance from this surface. Second, slower cooling rates lead to larger columns and greater proximity to the 'ideal' hexagonal pattern. However, we have seen that there is a wealth of detailed observations that can be made on columnar formations. Recent research gives hope that such work may yet grant us precise information on rock's cooling history.

References

Blackstone, D. L. 1963 'Columnar jointing in sandstone'. *Rocky Mountain Geol* **2** (1), 7–11

Boots, B. N. and Murdoch D. J. 1983 'The spatial arrangement of radom Voroni polygons'. *Computers and Geosci* **9**, 351–65

Bouchbinder, E., Mathiesen, J., and Procaccia, I. 2008 'Stress field around arbitrarily shaped cracks in two-dimensional elastic materials'. Preprint

Budkewitsch, P. and Robin, P-Y. 1994 'Modelling the evolution of columnar joints'. *J Volcanol Geotherm Res* **59**, 219–39

Burgess, A. http://www.geograph.org.uk/photo/4827

French, J. W. 1922 'The fracture of homogeneous media'. *Trans Geol Soc Glasgow* **17**, 50–68

Gilman, J. J. 2009 'Basalt columns: large-scale constitutional supercooling?'. *J Volcanol Geotherm Res* **184**, 347–50

Goehring, http://www.lgoehring.com/Starch_columns.html

Goehring, L. and Morris, S. W. 2005 'Order and disorder in columnar joints'. *Europhys Lett* **69**, 739–45

Goehring, L. and Morris, S. W. 2008 'The scaling of columnar joints in basalt'. *J Geophys Res* **113**, B10203

Goehring, L., Morris, S. W. and Lin, Z. 2006 'An experimental investigation of the scaling of columnar joints'. *Phys Rev* **E74**, 036115

Goehring, L., Mahadevanb, L. and Morris, S. W. 2009 'Nonequilibrium scale selection mechanism for columnar jointing'. *PNAS* **106**, 387–92

Grossenbacher, K. A. and McDuffie, S. M. 1995 'Conductive cooling of lava: columnar joint diameter and stria width as functions of cooling rate and thermal gradient'. *J Volcanol Geotherm Res* **69**, 95–103

Guy, B. 2010 'Comments on "Basalt columns: large scale constitutional supercooling?" by John Gilnam (JVGR, 2009) and presentation of some new data'. *J Volcanol Geotherm Res* **194**, 69–73

Hardee, H. C. 1980 'Solidification of the Kilauea Iki lava lake'. *J Volcanol Geotherm Res* **7**, 211–23

Huxley, T. H. 1881 *Physiography: An Introduction to the Study of Nature*. London: MacMillan and Co., 204

Jagla, E. A. and Rojo A. G. 2002 'Sequential fragmentation: the origin of columnar quasihexagonal patterns'. *Phys Rev E* **64** (4), 026203

Lodge, R. W. D. and Lescinsky, D. T. 2009 'Anisotropic stress accumulation in cooling lava flows and resulting fracture patterns: insights from starch-water desiccation experiments'. *J Volcanol Geotherm Res* **185**, 323–36

Lyle, P. 2000 'The eruption environment of multi-tiered columnar basalt lava flows'. *J Geol Soc* **157**, 715–22

Mallet, R. 1875 'On the origin and mechansim of production of the prismatic (or columnar) structure of basalt'. *Philos Mag* **50**, 122–35

Milazzo, M. P., Keszthelyi, L. P., Jaeger, W. L., Rosiek, M., Mattson, S., Verba, C., Beyer, R. A., Geissler, P. E., McEwen, A. S. and the HiRISE Team 2009 'Discovery of columnar jointing on Mars'. *Geol* **37**, 171–4

Müller, G. 1998a 'Experimental simulation of basalt columns'. *J Volcanol Geotherm Res* **86**, 93–6

Müller, G. 1998b 'Starch columns: analog model for basalt columns'. *J Geophys Res* **103**, 15239–53

Saliba, R. and Jagla, E. A. 2003 'Analysis of columnar joint patterns from three-dimensional stress modeling'. *J Geophys Res* **108**, B10, 2476

Tomkeieff, S. I. 1940 'The basalt lavas of the Giant's Causeway district of Northern Ireland'. *Bull Volcanique* **6**, 89–143

Toramaru, A. and Matsumoto, T. 2004 'Columnar joint morphology and cooling rate: a starch–water mixture experiment'. *J Geophys Res* **109**, B2, 2205–14

Xu, S. 1980 'Discussions on the morphological characteristics of two-layer columnar joints in basalt and their forming mechanism'. *Geol Rev* **26**, 510–15

Book review

Bull, William B. 2009 *Tectonically Active Landscapes*. Oxford: Wiley-Blackwell (ISBN 978-1-40519-012-1; hardback, 326 pages; £37.50)

Tectonically Active Landscapes is about the geomorphology of mountains, especially about how their morphology continually changes through fault uplift and propagation, erosion and stream flow. It does not discuss volcanoes or glaciers. Bull considers Himalayan rivers and middle-latitude mountain ranges in particular. He describes land surface features and brittle failure of rocks, although he also describes ongoing active metamorphism in the Himalayas. Deposition of sediments is not included, either offshore or lacustrine.

The book is well written: the author has an informal writing style, does not focus solely on the Western U.S.A., and covers extensively New Zealand's Southern Alps, along with Greece and the Himalayas. This book is a welcome change from most earth sciences textbooks. He is never pompous or long-winded. Almost every page spread has a visual aid, there are relevant tables, well-labelled diagrams and graphs, and many photographs, including satellite images, in monochrome; but there are no colour plates.

However, this is an advanced, specialised book. The Glossary does not cover all the technical terms. There are equations — for example the nonlinear transport law of sediment flux with gradient — though you can get the gist of their meanings from tables and graphs.

Geochemistry is not mentioned, nor is mountainous tropical jungle such as in Indonesia, where there is deep chemical weathering. Bull emphasises the long-term effects of repeated earthquakes on landscape, but does not include any seismic data on individual quakes. Landslip and earthquake damage to man-made structures is also excluded, so unfortunately this book is not directly relevant for civil and structural engineers. Earthquake-induced major events of sediment transport such as mudflows, seiches, dam collapses or tsunamis are also not covered, so the landscape techtonics described are rather less active than I had hoped for.

If you need to, or particularly want to, understand tectonic fault movement and mountain building, physical erosion, stream drainage and sediment movement on mountain slopes in mid-latitude ranges worldwide, then this is the book for you.

However, if you want geochemistry, disasters, sediment deposition, seismology, engineering in tectonically active areas, glaciers, tropical geomorphology, volcanoes, a bit of geology-based entertainment or an easy read with coloured pictures then try something else.

— Heidi Barnes, BSc (Hons) Open, BA Open, MIBMS (Member of the Institute of Biomedical Sciences)

The preparation of rock thin sections

Duncan Woodcock

Introduction

This paper documents the method that I use for preparing rock thin sections. Apart from a small rock saw, the method needs no specialised equipment (see the list in Appendix 2); indeed the method could be adapted to make thin sections without the use of a saw, albeit with considerably more effort required.

An earlier version of this paper was published in the *OUGSJ* several years ago (Woodcock 1993). Since then I have developed the methodology to the point that my original copy of the paper is covered in annotations and no longer easily legible to the occasional person who requests a copy. I offer this revised version in the hope that it might encourage those members who own a microscope to supplement their collection of thin sections and thereby extend their knowledge and enjoyment of petrography.

In outline the method consists of producing and preparing a thin slab of rock, attaching it to a microscope slide, grinding the slice to a standard thickness of 30µ and then attaching a cover slip. During the last 20 or so years I have made more than 2,000 thin sections from a wide variety of rocks using the methods described below. A high-quality thin section can usually be made from a hand specimen in one to two hours, depending on the type of rock. The production rate can be speeded up considerably by producing a batch of thin sections over a number of sessions; however, the method elaborated below is written on the assumption that a single rock thin section is being produced.

Method — Part 1: Production and preparation of a thin slab of rock

Step 1 First catch your rock! Aim to collect specimens of fresh rock, unless you have a particular interest in weathered material. Trim specimens in the field so that they can be held firmly in the vice of the saw. An ideal size and shape to aim for is *c.* 25mm × 50mm × 75mm with two parallel sides; however, not all rocks can be coerced into this ideal shape! The act of trimming the specimen in the field should uncover any flaws in the sample, giving the option of discarding it and selecting a more suitable specimen.

Step 2 Saw off a portion of the specimen so that the sawn surface is slightly larger than that required for the slice (for a 40mm long cover slip an ideal size of sawn surface is 24mm × 40mm). The sawn-off piece should be a minimum of 5mm thick.

Step 3 Without removing the specimen from the vice, try to cut a thin slab (thickness 0.5mm to 1mm if possible) of rock from the specimen. This may be very difficult or impossible with some rocks, but if it can be achieved it simplifies subsequent preparation. Assuming that the thin slab is available, proceed to (4); otherwise go to (6).

Step 4 Flatten and smooth one surface of the thin slab with 220 (medium grade) and then 600 (fine grade) Carborundum grits on suitable plate glass grinding plates. A small amount of water is added to the grit to produce a thin paste. Wash the thin slab thoroughly and scrub gently with an old toothbrush when changing from 220 to 600 grit and at the end of grinding. Allow the slab to dry and examine the smoothed surface in a good light: it should be flat and uniformly smooth; if in doubt repeat this step and re-examine. For some specimens, such as poorly cemented sandstones, it may be impossible to grind a suitable flat surface without grains 'pulling out'. Bulk impregnation of the specimen is required under these circumstances: see Appendix 1.

Method — Part 2: Attachment of the thin slab to a microscope slide

Step 5 Place the thin slab on a suitable hotplate or an inverted dry iron along with a clean glass microscope slide and a 50mm × 25mm × 6mm glass block. Raise the temperature to give a hotplate surface temperature of *c.* 110–120˚C and allow them to heat up. When hot the slab of rock is attached to the microscope slide with Lakeside Cement — a thermoplastic material supplied in short rods of solid, which starts to melt at *c.* 80˚C. Apply Lakeside Cement to the smoothed surface of the thin slab, the microscope slide and the glass block by touching the rod of Lakeside Cement onto the hot surfaces. Check the cement layer on the smoothed surface of the thin slab to ensure there are no bubbles produced by air escaping from the slab; continue heating if necessary.

Place the microscope slide over the thin slab and press slightly in the centre to ensure adhesion. Remove both to the cool edge of the hotplate. Immediately apply gradual pressure to the centre of the slice until any air bubbles present move to the edge of the slide — good lighting, from an angle-poise or desk lamp, is essential. Ensure that there is a rim of Lakeside Cement around the perimeter of the thin slab; this acts as a buffer to protect the edges of the slab during grinding. Mount the microscope slide on the glass block, again ensuring continuous contact. The glass block makes the subsequent grinding step much easier — avoiding damage to fingertips and minimising the chance of breaking the microscope slide.

Leave to cool.

Once cool, scratch a unique reference number on the opposite side the microscope slide to the rock slice, using a hardened steel scriber, a suitable piece of quartz or any other point hard enough to do the job. Record this reference number, along with the details of the original specimen, in a suitable logbook. When cold the mounted thin slab is ready for grinding to 30µ thickness (Step 7).

Step 6 If the thin slab is not available, do steps (4) and (5) with the portion of the specimen from (2). Mount the assembly of glass block, microscope slide and rock in the saw vice and make a cut parallel to the microscope slide so as to leave a thin slab of rock 0.5mm to 1mm thick attached to the slide. This may require a bit of adjustment to get it right! If the cement has locally parted from the slide, re-establish continuous contact by warming the glass block on the hotplate at 90˚C.

Method — Part 3: Grinding to 30µ thickness

Step 7 The thin slab is now ready to be ground. However, if the slab has been left overnight or longer, I carefully reheat it until the Lakeside Cement is just soft (test by pressing a fingernail into the rim of cement around the perimeter). Grind the thin slab with 220-grit Carborundum until feldspars and/or quartz show blue

© OUGS ISSN 0143-9472

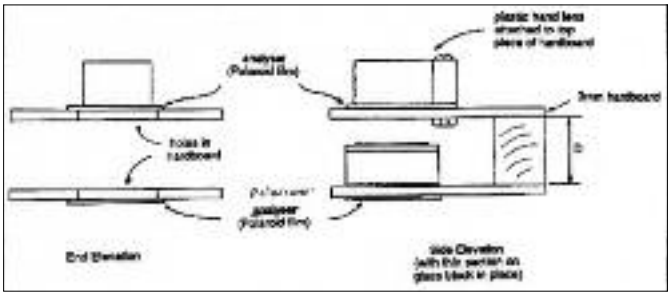


Figure 1 The 'wet microscope'. Dimension D to suit the focus of a hand lens; all other dimensions are non-critical.

second order interference colours (use the 'wet microscope' — see Fig. 1). When grinding, aim to use the whole of the surface of the glass plate so that it wears out evenly. Try to maintain an even thickness of the slab as grinding proceeds; any unevenness can be corrected by judicious use of the edge of the grinding plate.

As grinding proceeds the grit gradually becomes less abrasive and additions of fresh grit are required. After a couple of additions it is probably best to wash all the spent grit off the glass plate and start afresh; however, I always aim to do the final few minutes grinding with partially spent grit, as it allows a slower — and thus more controlled — approach to second order blue. Spent grit can easily block the kitchen drain, so I wash this into a bucket for recovery (I use it in a Vibrolap for polishing larger slabs of rock).

Frequently rinse off the thin section to check the thickness, especially as the correct thickness is approached, using the wet microscope and by direct examination in transmitted light — the latter often gives a good confirmation of uniform thickness. Remember that rocks vary considerably in hardness; this step can take anything from 10 minutes to half an hour or more. From experience, rinsing with warm water rather than cold seems to prevent the Lakeside Cement from becoming brittle.

Step 8 Rinse the thin slab thoroughly in water and complete grinding with 600-grit Carborundum to produce a slice of 30µ thick. At this thickness quartz shows interference colours up to a faint yellow ('straw yellow'). The majority of feldspars show grey and white interference colours, although high An plagioclase can be up to yellow. In ultrabasic rocks, the maximum interference colours of augites do not quite reach second order green in a 30µ section, so a second order blue is about right. Rinse and dry the slice when it has been ground to the correct thickness.

While grinding with 600-grit, inspection of the section may reveal some unevenness in thickness. If this occurs, I draw a 'birefringence map' of the thin section to help me selectively grind those areas that are too thick. My 'birefringence map' is nothing more than a sketch of the outline of the thin section with an indication of the distribution of interference colours displayed by a chosen key mineral, usually quartz or feldspar. An example of a 'birefringence map' for quartz grains is shown in Figure 2: in this example the top left hand corner is much too thick and can easily be corrected by the selective use of a corner of the grinding plate.

Method — Part 4: Preparation for attaching a cover slip

Step 9 Place the glass block on the hot plate and raise the temperature until the microscope slide, together with the slice, can be removed from the block (a temperature of 120˚C is adequate,

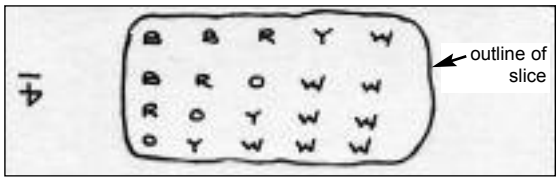


Figure 2 Typical 'birefringence map':

W = white (target)	*1st order*
Y = yellow	
O = orange	
R = red	
B = blue	*2nd order*

with removal possible after around five minutes). Place the slide face downward to cool completely, taking care not to scratch the freshly ground face.

Step 10 Remove the layer of Lakeside Cement from the underside of the microscope slide with an old razor blade. Trim the rock slice to a shape suitable to the size of the cover slips to hand — I use an old jackknife for this together with an old microscope slide as a convenient straight edge. All rock and cement outside of the trimmed section is removed with an old razor blade. Wash under running water to remove all bits of cement and rock. Dry the slide and slice on the hot plate at 90˚C or so. Remove and cool.

Step 11 Check that the ground surface of the slice is free from all bits of rock and cement,s as well as from any dust or fluff. Apply a layer of diluted nail varnish (1 part *clear* nail varnish to 3 parts nail varnish remover) to the surface of the slice to within 1mm of the edge. Paint over any small holes in the slice but paint around any larger ones. Dry on the hotplate at 90˚C. The slice is now ready to be covered with a cover slip.

Method — Part 5: Attachment of a cover slip

Step 12 The cover slip is attached to the slice with Canada Balsam — a viscous liquid that hardens on exposure to air or on heat treatment. Aim to work in as dust-free an environment as possible to minimise the incorporation of extraneous materials between the thin section and the cover slip — some fibres can be distractingly colourful between crossed polars!

Place a clean cover slip on the hot plate alongside the slice and microscope slide. Apply Canada Balsam with a clean 5mm glass rod to the slice. Raise the temperature of the hot plate to 110–120˚C to cook the balsam — this usually takes two to three minutes. Temperature is fairly critical: too low a temperature and the balsam does not cook properly; if the temperature is too high the balsam starts to 'smoke' and small bubbles are generated between the slide and the slice. In the absence of an accurate temperature indication, a drop of water should boil fairly quickly but not 'dance' on the surface of the hot plate. Check that the balsam has cooked by pulling off a bead with a preheated pin, cooling it rapidly and checking that it is plastic rather than 'sticky': you should just be able to impress the cooled bead with a finger nail. On balance it is better to undercook the balsam. While cooking, the surface of the balsam should appear optically flat: any dust or fibre that lands on the balsam is immediately visible and can be carefully removed with a pin.

When the balsam is cooked, apply the cover slip to the slice hinge-wise and press down gently with a matchstick to remove all air bubbles. Use an anglepoise lamp or desk lamp to give the best possible local illumination. As the cover slip hinges down onto the balsam-covered thin section the ideal is for the interface between balsam and air on the underside of the cover slip to move slowly and coherently across the width of the cover slip and thus minimise the number of air bubbles trapped under the cover slip.

Examine the thin section carefully for trapped air bubbles. In reflected light these should appear light against a darker background. Note the location of any bubbles, return the thin section to the hot plate and use gentle pressure on the end of a match stick to attempt to 'walk' each bubble to the edge of the cover slip and into the exuded surplus balsam, where they should stay.

Step 13 The microscope slide often becomes scratched (and occasionally broken!) during the grinding stage. If you wish to transfer the finished thin section to a new microscope slide (and thereby produce a much more professional end result), the procedure in Step 12 is modified as follows:

Place a new clean microscope slide, cover slip and the business end of a 'pusher' — an 8mm wide lolly stick with one end cut square makes an ideal pusher — on the hot plate next to the slice. While the hot plate is still at 110–120˚C, apply Canada Balsam to the new slide, the rock slice and the area of the old slide between one edge and the adjacent margin of the slice. Cook the balsam and fit the cover slip as described in Step 12. Carefully push the slice and the cover slip towards and over the layer of balsam between the slice and the edge of the slide until the slice and cover overhang but do not droop — keep an overlap of at least 3mm between the slice plus cover slip and the slide. Lower the slice together with the cover slip hinge-wise onto the layer of balsam on the new microscope slide, gradually pushing the slice and cover slip clear of the old microscope slide. Remove any air bubbles by the gentle application of pressure with a matchstick. Adjust the position of the slice and the cover slip relative to the microscope slide by using the matchstick: pressure applied near an edge of the cover slip should, for example, make the slice move forward relative to the cover slip. When positioning is satisfactory, gently press down on the cover slip and allow to cool. Re-label the new microscope slide with the same reference number as the old one.

Step 14 Use a heated straight-bladed knife to remove the exuded surplus balsam away from the immediate edges of the cover glass. Take care not to damage the edges of the cover slip: allow the hot knife to melt into the surplus balsam at the edge of the cover slip and then scrape outwards. When completely cool, remove this balsam together with any on the top of the cover glass with an old razor blade.

Step 15 Clean the thin section with methylated spirits applied with a small pad of cotton wool. Wash with soap and water. Rinse, dry and label to taste.

Conclusion

The procedure probably looks pretty complicated. However, it is easier to do than to describe! With a little practice one can produce good thin sections that are perfectly usable for petrological examination. Do not expect your first attempts to be perfect; on the other hand, do not give up too soon. I recommend using the same rock for your first few attempts: this gives you the best chance of building on the experience of previous attempts. A dolerite, such as Whin Sill material, is an excellent starting material.

There are of course many other ways of making thin sections. Most university geological departments use epoxy resins, such as Petropoxy, in place of Lakeside Cement and do the bulk of their grinding by machine. Another alternative is to spray the uncovered thin section with a clear gloss varnish rather than finish with a cover slip. Descriptions of other procedures for making thin sections can be found in MacKenzie *et al.* (1984), Clarke (1985) and in Woodhouse (1986).

References

Clarke, J. 1985 'Building a polarising microscope and cutting thin sections'. *OUGSJ* **6** (2), 39–42

MacKenzie, W. S., Donaldson, C. H. and Guilford, C. 1984 *Atlas of Igneous Rocks and Their Textures*. Harlow: Longmans

Woodcock, D. C. 1993 'The preparation of rock thin sections'. *OUGSJ* **14** (1), 21–4

Woodhouse, N. R. 1986 'Preparation of rock thin sections at home'. *OUGSJ* **7** (1), 5–6

Appendix 1: Treatment of friable materials

Bulk impregnation is required for very friable materials such as poorly cemented sandstones: this procedure can be carried out by soaking the specimen in a dilute solution of Araldite in acetone. Over the years, I have extended this treatment to any slabs that I am not completely happy with after grinding with 600-grit Carborundum in step 4. I now routinely treat all schists, together with any igneous rocks that may lose grains during grinding; large phenocrysts of pyroxene or amphibole are particularly prone to disintegration if their sections contain two well-developed cleavages. I have also used Araldite solution to consolidate loose sand and then subsequently made a thin section: Araldite thus takes its place alongside the more usual quartz, calcite and haematite cements!

The recommended procedure is as follows:

Mix Araldite adhesive and hardener (the overnight setting variety) and dissolve at least one part in 50 parts of acetone. I generally mix the Araldite and acetone in a clean jam jar at least a week before required. The Araldite adhesive appears to dissolve quickly, but the hardener dissolves much more slowly. A daily inspection and swirl round seems to suffice. I decant the solution into a clean jar ready for use. Once produced, the solution has a shelf life of a couple of months.

Cut a 40mm × 22mm × 10mm (approx.) piece of rock from the hand specimen and immerse in the solution. Leave overnight.

Dry out and allow the Araldite to set, initially at room temperature and then in a warm oven. For really friable specimens it is worth repeating the immersion and drying process until no bubbles are displaced when the dry piece is immersed in the solution.

Allow the Araldite to set really hard by a combination of neglect (around a month) or repeated trips into the oven warming drawer after tea for a week or so. When hardened, the Araldite can be sawn and ground just like rock.

Stick one 40mm × 22mm side to a glass block with Lakeside Cement. Mount the block in the saw vice and cut the piece of rock in half to give two slices *c*. 4mm thick.

Grind the freshly cut surface with 220- and 600-grit Carborundum as in the procedures described in steps 7 and 8 above. Araldite is isotropic between crossed polars.

This procedure seems to minimise grain pull-out and enables the production of thin sections that display the porosity of the original specimen.

Appendix 2: Equipment and materials required

1. Diamond-bladed rock saw. I use a saw with a 6in water-cooled/lubricated blade. Smaller blades are probably not sufficiently robust. Larger blades are usually lubricated with a cutting oil, which needs to be washed off thoroughly in detergent solution: this can be practically impossible if the specimen is at all porous. Given a choice, use a water-cooled rock saw to avoid any problems due to retention of oil.
2. Hot plate, capable of some control on a low heat, such as an inverted dry iron or a cooker with a ceramic hob
3. A 'wet microscope': constructed from a plastic hand lens, two small pieces of Polaroid, and a hardboard holder (*see* Fig. 1)
4. Anglepoise lamp or other suitable desk lamp
5. Two glass plates, *c*. 300mm square and 6mm thick (standard plate glass)
6. 50mm × 25mm glass blocks, 6mm thick
7. Carborundum (silicon carbide abrasive) grits: 220 and 600 grades
8. 'Lakeside 70C' cement
9. Microscope slides: standard 76mm × 25mm
10. Canada Balsam
11. Microscope slide cover slips (the standard size is 22mm × 32mm, but it is worth having some 22mm × 40mm cover slips as well)
12. Short length of 5mm glass rod
13. Lolly stick: flat type — for pusher
14. Colourless nail varnish and remover
15. Straight-bladed dinner knife
16. Hardened steel scriber or suitable piece of quartz to scratch glass

N.B. Canada Balsam has a tendency to go off if left exposed to air or light. It is best stored in a small wide-necked glass jar and kept in the dark with the lid taped round with insulating tape. I find that 25g is sufficient for about 100 thin sections with routine transfer of the finished thin section to a new microscope slide.

Appendix 3: Equipment and material suppliers

1. 'Lakeside 70C' cement

One box (minimum order) contains 20 cubic inches in about 18 'sticks', obtainable from:

Production Techniques
13 Kings Road
Fleet, Hants GU13 9AU
01252 616575; www.production-techniques.com

Do not be put off by their on-line catalogue, just ring them up!

2. Canada Balsam

Available in 25g and 100g lots. Check that it is 'filtered for microscopy' grade. My current suppliers are:

Scientific Glass Blowing Co. Ltd
163 Higginshaw Lane
Royton, Oldham
Lancashire OL2 6HQ
0161 621 4700 or 0161 655 1505; sales@sciglass.co.uk

They can also supply microscope slides, cover slips, microscope slide boxes and much more.

3. Carborundum (silicon carbide abrasive) grit

Available as 220-grade (500g lot) and as 600-grade (150g lot) from:

Manchester Minerals
Georges Road
Stockport, Cheshire SK4 1DP
0161 477 0435; http://www.manchesterminerals.co.uk/

I apologise for the 'NW' bias to the above suppliers; those of you in other areas may find more convenient sources.

Appendix 4: Some health and safety aspects of thin section production

This appendix contains a few tips; it is not necessarily comprehensive and does not replace careful study of all health and safety information provided by suppliers of equipment and chemicals. No liability is accepted by the author; users follow the procedure at their own risk.

1. Hot surfaces

Work in close proximity to hot surfaces, such as an upturned iron is unavoidable and requires some care and manual dexterity. The development of 'asbestos fingers' over the years has helped. I always put a note on the top of the hot iron when it is left to cool, principally to warn other members of the family.

2. Rock saws

I wear light eye protection and ear defenders while slicing rocks. The saw blade grinds rather than cuts, so minor abrasions are possible if the saw is used carelessly.

3. Glass

Beware of sharp edges if a microscope slide, cover slip or even a thinned grinding plate breaks. Ensure that your supplier of glass plates and blocks removes the sharp edges for you before use.

4. Flammable hazards

Methylated spirits and acetone are both flammable, so beware!

5. Toxic hazards

Methylated spirits is toxic: I use kitchen washing up gloves when cleaning off the finished sections (step 15) and ensure that I have adequate ventilation while doing this task.

Appendix 5: Thin section production: the bare essentials

If the method outlined in this note looks too complicated, here is a method that will produce useable thin sections with almost no specialist equipment or materials. Apart from microscope slides, all the requirements are probably already to hand or can be obtained from your local hardware shop.

Step 1 Chip a flattish piece off the edge of the hand specimen. A chip about 10mm × 20mm is a good size.

Step 2 Flatten one side of the chip on moistened 'wet-and-dry' Carborundum paper, using a coarse grade (100- to 200-grit) to get a flat surface; then use a finer grade (400- to 600-grit) to get a smooth surface. A piece of window glass provides a suitable flat surface on which to rest the Carborundum paper. Rub one side of the microscope slide on the finer grade Carborundum paper to produce a smooth frosted effect. Wash both the rock chip and the microscope slide and allow them to dry thoroughly.

Step 3 Mix a quantity of Araldite (the overnight set variety, not the 'rapid-set' variety) sufficient to stick the rock chip onto the microscope slide. It is possible to minimise the amount of air entrained if the Araldite is mixed slowly on the frosted surface of the microscope slide. Leave the Araldite to stand for about 20 minutes and then carefully lower the flattened side of the chip onto the Araldite. A slight twisting motion and some pressure is usually sufficient to expel any air bubbles from the Araldite layer.

Step 4 Hold the chip in place on the microscope slide with bulldog clips and leave for at least 24 hours to allow the Araldite to set hard. Ensure that the bulldog clips cannot themselves become stuck to the chip or to the microscope slide!

Step 5 Grind away the bulk of the thickness of the rock chip using a coarse grade of Carborundum paper. The paper will become blinded with 'mud' as grinding progresses: a quick scrub under the tap with an old toothbrush helps in this case. As the rock chip thins, wear on fingers can be minimised if the top of the microscope slide is kept dry; there should then be sufficient friction between the fingers and the top of the slide to enable it to be moved on the moistened Carborundum paper.

Step 6 As the thin section approaches the required thickness, change to a fine grade of Carborundum paper. Continue grinding, checking the thickness frequently. Take care to rinse and dry the thin section before placing it on the microscope stage.

Step 7 The completed thin section can be protected with a layer of varnish or it can be left bare. In any case, do not forget to label it!

Acknowlegement

Two people in particular have helped greatly over my years of thin section production. Alex Herriot, now deceased, introduced me to the art of making thin sections and was a superb petrography tutor. My wife, Denise, regularly allows our kitchen to be temporarily converted into a petrographic workshop.

Author

Duncan Woodcock is a senior process engineer with ABB Engineering Services, an OU graduate and an ongoing OU student.

Book review

Coe, Angela L., Argles, Tom W., Rothery, David A., and Spicer Robert A.; edited by Angela Coe 2010 *Geological Field Techniques*. Milton Keynes: Wiley-Blackwell in association with The Open University (ISBN 978-1-4443-3061-8 (hardback) and 978-1-4443-3062-5 (paperback); xii + 324pp; hardback £80.00, paperback £24.99)

companion website www.wiley.com/go/coe/geology)

For me fieldwork is the most enjoyable part of geology; it reinforces how diverse and exciting different landscapes can be. The aim of this book is to equip Earth Science students with up-to-date geological techniques that confer appropriate field observations within the given time frame.

In brief, the book advises students on making observations, recording findings and how to collect different types of field data. In addition, there are sections on the recording of sedimentary, igneous and metamorphic rock features, as well as structural geological features. Of particular interest to the student is the guidance on notebooks, graphic logging and how to use a compass-clinometer. Fieldworkers are encouraged to be clear about why they are undertaking the fieldwork, so that they collect the appropriate data and specimens sensitively, and with respect to conserving the location for future fieldworkers.

This book is not a passive read and there is a great deal of assumed knowledge, which is appropriate for students at course Level 2 or above. The terminology is up to date, easy to understand and yet is not diluted in content. The collaboration of the four authors means writing styles vary, but overall they blend very well to bring their expertise together and make this book a stimulating read that leads you on to wanting to know more about Earth Science.

The main text and the extensive appendix have numerous beautiful illustrations, figures and colour photographs, which make this a visually pleasing book. The colour coding of each page highlights and helps locate a topic fairly quickly (by looking at the page edges), and this feature becomes more useful on a second read.

The companion website that complements the book is especially useful, providing a closer view of fossils, and enabling the worker to zoom in on the fine details that would not be seen by eye alone.

I feel that the book accomplishes its main stated objective, which is to prepare the undergraduate student with a comprehensive range of geological field techniques. The amalgamation of figures, tables and diagrams bound together is both valuable and convenient. The personal sketches and field notes are greatly appreciated because they do help set a standard from which students can improve their own field notebooks. Finally, the font used and size is comfortable to read and the layout allows one to make notes and to annotate the text easily.

I feel that the cost of this book is reasonable and that it is a valuable addition to my own little library.

— Lorraine Clarke, OU Earth Science student

Book review

Brook, Anthony (ed) 2010 What on Earth is Under Sussex? Journal of the West Sussex History **77** (2008–09). Worthing: West Sussex Archives Society (no apparent ISSN; paperback, 96pp; £11.20 [incl p&p], available from Guildbourne Publishing, Worthing, West Sussex BN11 4BQ)

This issue of the *Journal of the West Sussex History* is devoted to the history of geologic inquiry in West Sussex. It is as much about the people who have discovered the geology of West Sussex as it is about the geology itself.

This is Part 1 of an intended two-part publication. It comprises the first seven papers and is to be followed by Part 2 with eight more papers (the papers for Part 2 are also listed in the contents). The authors are from all over the world, each having done former work on West Sussex geology.

The papers in Part 1 are:

'Taking the waters at Brighton, 1750–1850', John Mather (Royal Holloway, U London)
'Rev. Charles Wilton and his pre-emigration geological investigations in West Sussex', Wolf Mayer (Australian National U)
'Gideon Mantell and the Brighton Press, 1834–1838', John Cooper (Royal Pavilion and Museums, Brighton)
'Gideon Mantell and the art of seeing pebbles', Melanie Keene (Darwin College, Cambridge U)
'Herbert Toms and the geological folklore of Sussex', Christopher Duffin
'Edward Alfred Martin and "the glaciation of the South Downs" ', David Bate (BGS)
'Martin Venables and the Natural Science and Archaeology Society of Littlehempton, 1933–1938', David Bone (West Sussex Geol Soc)

There is a wealth of black and white photographs and lithographs, line drawings, charts and diagrams to illustrate the topics. The inside front cover has a useful full-colour geological map of East and West Sussex; and the back cover has a colour portrait of the pioneer palaeontologist Gideon Manrtell (inside) and colour examples of four of his drawings of 'pebbles' with fossils, from his *Thoughts on a Pebble* (1849). The issue is admirably produced on a low budget, and includes an index to enable the reader to quickly re-locate topics of interest. The numerous references at the end of each article will enable a keen reader to pursue the topics further.

For anyone living in this area of southern England this geological issue (and its up-coming companion) will provide a useful record of the development and overview of West Sussex geology and how it fits into the geology of Britain.

— David M. Jones, BA UC Berkeley, MA, PhD UC London, BSc Open

---

Book review

Burek, C. V. and Prosser, C. D. (eds) 2008 *The History of Geoconservation*. London: The Geological Society (ISBN 978-86239-254-0; hardback, 312 pages; £60)

This book is a collection of papers exploring the origins and concepts of geoconservation, both in the UK and more widely in Europe and Australia. The development of global conservation initiatives such as World Heritage sites and the establishment of Geoparks is explored, as well as the role of organisations such as the Geologists' Association (GA) and the British Geological Survey (BGS). The need for local voluntary geoconservation groups such as Regionally Important Geological Sites [groups] (RIGS) and Local Geodiversity Action Plans is also explored.

Geoconservation is a relatively new concept and investigating the origins of geoconservation presents something of a problem because there is no established definition of the field. Perhaps it could best be defined as 'action taken to conserve geological and geomorphological features, processes, sites and specimens'. Geologically interesting sites, for example The Giant's Causeway, had been identified as early as the 17th century, but the idea that such sites need to be conserved has developed only slowly.

In Britain there were very few geological reserves before the middle of the 20th century and no legislation to protect them. Most land in 19th-century Britain was owned by comparatively few wealthy people, so there were few opportunities for conservation, as there was no legal basis for doing so other than by land ownership. In contrast, in the 19th century the U.S.A. had many more protected sites, because westward expansion had resulted in federal land holdings, and the desire to save important sites led to the establishment of National Parks protected by legislation.

The economic growth and social change that occurred in the second half of the 20th century in many parts of the world led to increased leisure time and tourism, and to enhanced awareness of the natural world. Loss of the countryside to development and the ability to view our planet from space increased awareness of the fragility of the natural environment, and by the 1990s the Earth Summit held in Rio de Janeiro had placed the environment on the political agenda. Today it is climate change that makes us aware of the damage we can do to the world in which we live.

This book is primarily a look backwards at the development of geoconservation, but it does demonstrate the need to plan for sustainable development in the future; the balance between geoconservation and geo-exploitation will need to be addressed.

Definitely a book worth reading.

— Lesley Laws, BSc (Hons) Open (Geoscience)

Book review

Wilson, Peter 2010 *Lake District Mountain Landforms*. Lancaster: Scotforth Books (ISBN 978-1-90424-456-1; hardback, xiv + 210 pages; £20)

Being an inveterate fell walker in the Lake District during the past 40 years, I have collected numerous books on Lakeland geology and landscape studies.

This book comprises 10 chapters, emphasising the fact that the Lakeland landscape is primarily derived from recent glaciation of older formed rocks. Wilson therefore begins by defining 'geomorphology' and gives a short summary of how it came to be a specialist study and how it is applied.

Chapter 2 describes the Lake District's geology — its rocks. He covers how they were formed and when; and includes an excellent geological base-rock overview map and chart of the time periods and rock types.

Chapter 3 builds on this base to describe the evidence for preglacial landscapes in The Lake District. Wilson points out the telltale remnants of former landforms before the last Ice Age moulded and scoured the present Lakeland valleys, crags and hills.

Chapter 4 comes to the heart of Lakeland landforms by introducing the geology of glaciation, and the associated and related processes. This is a general discussion that introduces and defines the basic glacial geological terminology. (It could serve as an admirable summary of the detailed chapters in Bennett and Glasser 2009, reviewed elsewhere in this issue of the *OUGSJ*.) It confines its examples, of course, to the Lake District, but covers all the principal processes of glaciation, evidence and landforms.

Chapter 5 covers periglacial processes and landforms. Wilson defines the terms, including the coining by present-day geologists, and use of, the term 'periglacial' for a group of cold-climate, frost condition geomorphology. Again, Wilson naturally confines his examples to Lakeland while providing a clear understanding of cold-climate processes and the resulting landforms and rock shapes. These processes continue in the Lake District today.

Chapter 6 focuses on hill slopes and shapes: crags, land- and rock falls and other mass movements of material, past and present, in Lakeland.

Chapter 7 focuses on Lakeland's lakes, tarns and rivers: how these shaped and continue to shape Lakeland landscape in our post-glacial (or inter-glacial?) times. Although again Lakeland-confined, it is a useful revision of fluvial and lacustrine dynamics and environments for any geologist.

Chapter 8 is specific to the limestone landforms of Lakeland, all of which form a ring nearly surrounding the higher mountainous areas of the Lake District. These landforms are especially well represented in Lakeland's south and east.

Chapter 9 illustrates the rounded approach of Wilson's book by covering the 'man-made' landforms in the Lake District. No true geomorphologist can ignore the impact of humans on any landscape, especially in Britain, where almost no area has been left untouched and heavily affected by human endeavours. Perhaps only the Cairngorms remain as an example of meagre human effects. This is a brief chapter, but does touch on the farming, herding and mining interests in Lakeland from late prehistoric to modern times.

Chapter 10 is a mere two-page 'Finale' or parting thought. Concentrating on the Langdale Pikes, Wilson uses them to urge his reader to observe and 'tease out' the history of a landform by observing it in large-scale view and examining it in small-scale focus — something we OUGS Members love to do!

The book is filled with superb colour photographs illustrating the landforms and evidence of the processes described. There are also colour schematic diagrams to explain them. The only 'fault' (and I use the term loosely) I would venture is the lack of a 'political' map of the Lake District to complement the geologic map, although several important place-names are included on the latter.

The book concludes with a nine-page 'Further Reading' list, broken into topical sections that basically mirror the chapter topics. There is a further useful page listing geological societies that concentrate wholly or in part on the Lake District; and lastly a six-page index in a type-face about three points smaller than the main text — so it adequately covers the names, places and topics in the book.

This book is an admirable summary or overview of the entire area, of its geology and physical geography in a book that comprises only just over half its pagination in text. I read it in two sittings. At £20 for a durable hardback it is a bargain and I have already bought myself a copy.

— David M. Jones, BA UC Berkeley, MA, PhD UC London, BSc Open

---

Book review

Smith, Alan 2008 *The Ice Age in the Lake District: the Landscapes of Cumbria No. 3*. Keswick: Rigg Side Publications (ISBN 0-95-446792-2; paperback, 60 pages; £3.99)

This is a slim, A5-format book that is eminently readable by specialist and interested lay readers alike. It is lavishly illustrated with 41 colour photographs and 22 other diagrams, plus a short, but most useful, glossary of specific terms on glaciation as used in the book.

Alan Smith himself lives in Keswick and the whole book, like so many of his writings on Lakeland, conveys his extensive knowledge and deep affection for this beautiful area of the British Isles.

After a brief, but lucid, introduction he goes on to explain the fluctuations in climate over the past 2.6Ma and how ice ages originate. Then comes more detail about the last glaciation and about the Lakeland Ice Cap in particular.

Sections on the glacial features of Cumbria and on the lakes themselves follow. Did you know that Wastwater is the deepest, and that Lake Windermere is the only one with the word 'Lake' in its actual name?

Next come explanations of cirques, the lowlands and meltwater features. There is a chapter on the final stages of the glaciation, a passage on periglaciation, another on Limestone Pavements and one on changing sea levels.

Lastly there is an account of 'paraglaciation' — a term new to me — but which includes rock slope failures. There is then a page about Life in Lakeland.

Altogether this is a fine, comprehensive account of the subject matter and easily worth twice the price. If you are a devotee of the Lake District, or even mildly interested, this one is a must.

— Norma Rothwell, OUGS Vice President

Editor's notes to contributors

Following are guidelines for the submission of articles to the *OUGS Journal*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Journal*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention (I will probably spot them anyway) so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Journal* articles

As *OUGS Journa*l Editor I do not want the publication of your paper to be more work than is necessary for you (or for me!). Your paper need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material.

Regarding papers from the presenters of lectures at the OUGS Symposium, all OUGS members are grateful to you for presenting a talk at the OUGS Annual Symposium, and for agreeing to submit a version of your talk for publication in the *Journal*. The purpose of this is to make your information available to OUGS members and others who could not attend the symposium. As OU students and OUGS members we enjoy hearing and learning the information these symposia bring to us.

All that is necessary is the following:

• A Word (or compatible) file of the text: There is no need for you to attempt to format the text in any way using tools in Word or other word-processing software. I will do the page layout format in the *Journal* house style, using dedicated publication-industry-standard page-layout software (QuarkXPress). However, feel free, if you wish, to use **bold** and/or *italics* to indicate headings and subheadings so that I can set these into house style.

I do not require a hard copy, but if you need to point out special characters or attributes in your paper, it may be a good idea to send one with these items marked up or otherwise highlighted. Otherwise I can accept electronic files attached to an e-mail, or files on a CD.

• Each illustration, chart, graph, map or other illustration as a separate digital file in high resolution: 350dpi minimum for colour or half-tone images; 1400dpi for line illustrations. Tables composed in Word or Excel are fine, as they are just text. A rough guide to the number of figures in an article is 10 to 15. Obviously as a symposium presentation speaker you might have shown numerous slides, so please use your best judgement on the number to include with the paper to be published — again usually 10 to 15 is a rough guide. *Please note that figures are normally printed in greyscale in the* OUGS Journal*, except Moyra Eldridge Photographic Competition winners' photographs.*

• Please be sure that we have permission to publish any illustrations that are not yours: Also, please give me the appropriate information to cite in acknowledgement in the figure caption; and please tell me in writing or in an e-mail message that you have obtained the permission necessary for each illustration in your article that is not yours.

As the author, this responsibility is yours.

• Please do not embed your illustrations in Word picture boxes within the text: All that is necessary is to indicate, by a reference within ( ) or within [ ] in your text, where the illustration should go.

• You can submit the material as attachments to e-mails to me or send it to me on a CD: I am on BT Broadband, so I can receive large files. It is usually best to attach only a few illustration files each to several e-mails. This applies especially to large files of photographs, charts and graphs.

• Where appropriate, cite your sources, or make it clear that a statement is a supposition, or solely your own view or opinion. We use Harvard style citations in the text: (author date, pages), e.g. (Jones 2004, 51–3); and your sources or references should be listed in alphabetical order by author and date at the end of your article. You need to list the author, date of publication (or of access to a web site), full title, periodical volume and number, or place of publication and publisher, and page numbers.

If you miss out anything, I will ask you for it.

If your list includes items not cited in your text, it will be called 'Sources'; if all items in your list have been cited in your text, it will be called 'References'.

That really is it! The editing and page layout are my job, so let me do it for you. I will communicate with you as necessary as I do this, with queries or difficulties with any formats, special symbols, characters, etc, as is the task of any editor.

For you really keen authors, regarding grammar and spelling I use:

Butcher, J. 1992 *Copy-Editing: The Cambridge Handbook for Editors, Authors and Publishers* (3 edn). Cambridge: Cambridge U. P.

The Oxford English Dictionary

The Penguin Spelling Dictionary 1990. London: Penguin Books Ltd

Ritter, R. M. (ed and comp.) 2000 *The Oxford Dictionary for Writers and Editors* (2 edn). Oxford: Oxford U. P.

Ritter, R. M. (ed and comp.) 2002 *The Oxford Manual of Style*. Oxford: Oxford U. P.

Please contact me at any time about your paper:

Dr David M. Jones, *OUGS Journal* Editor;
journal@ougs.org

The Open University Geological Society (OUGS) or its Journal Editor, accept no responsibility for breach of copyright. Copyright for the work remains with the author but copyright for the published article will be that of the OUGS.